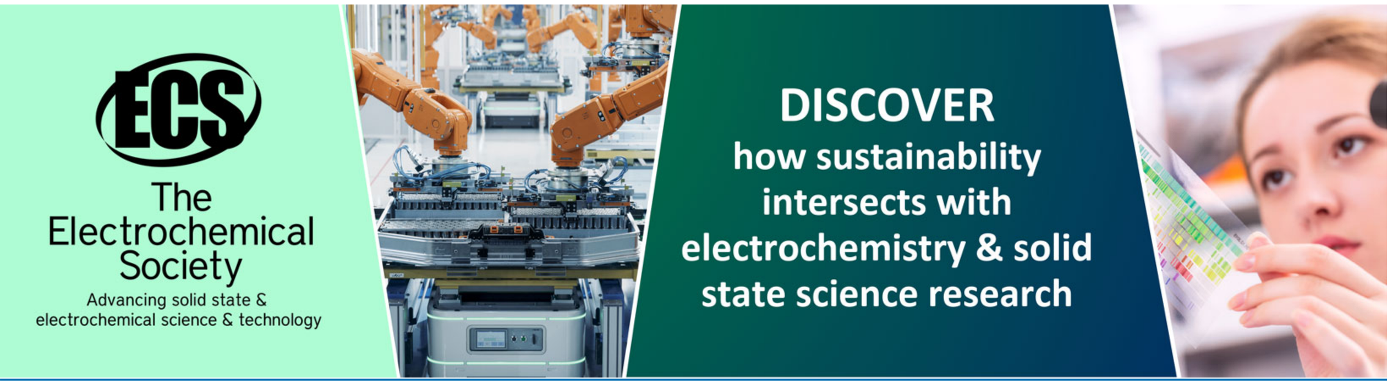
Games for Quantum Physics Education



Games for Quantum Physics Education

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Abstract. As the second quantum revolution comes to pass with its potential to revolutionize our lives, it becomes increasingly relevant to educate the public about quantum mechanics. Quantum literacy is also a formidable challenge and opportunity for a massive cultural uplift, since it fosters the possibility for citizens to engender their creativity and practice a new way of thinking. However, quantum theory is highly counterintuitive, manifesting in a reality we have no direct experience of, and represented by mathematically difficult formalisms. Here, we propose that games can provide a playground for engaging forms of experimental and symbolic literacy accessible to anyone. We discuss the theoretical foundations underlying this idea in the framework of a global educational strategy, illustrate existing examples of its implementation along different dimensions related to educational, citizen-science, and age-related contexts, and envision future challenges.

1. Introduction

The rapid change in science and technology witnessed in the last decades has significantly increased the awareness of decision makers and education stakeholders of the need to strengthen the connection between research, education, and outreach. As the first experiences of scaling up the latter are being evaluated a shift in focus "outreach" to "engagement" is starting to take place, in order to reflect the need for a two-way interaction where all parties can contribute to and benefit from the learning process [1].

Along these lines, increasing public awareness of quantum physics is becoming a priority as an extraordinary opportunity to develop general physics intuition and innovate physics learning/teaching processes in all school and University degrees. This is especially true amidst the second quantum revolution [2], where new Master and Bachelor of Science programs for quantum information and engineering are flourishing worldwide [3-5], and the recent development of a quantum competence framework has laid out a set of knowledge goals for the future quantum-literate workforce [6]. In fact, while quantum technologies and solutions are being developed for sensing, simulation, computing, and networking purposes, there is the potential for incredible economic development with enormous potential societal impacts from revolutionizing our daily lives to deeply changing the labor market [7]. Both in order to ensure the education recruitment pipeline and to build positive public attitudes of adoption, there is an urgent need to build up awareness on quantum technologies, their benefits and potential drawbacks, and increase the level of quantum literacy among students and general public. Also, like other forms of socio-scientific, collaborative knowledge creation processes, collaborative work around building Quantum Science and Technology (QST) solutions represents a great opportunity for smart community building, as it trains to out-of-the box thinking, with creativity and originality [8].

Scientific thinking hinges on analyzing facts and creating understanding, then formulating these with dense mathematical language for experimental verification, fact checking, and further development. Within classical physics, learner's intuition can be educated via classroom demonstrations of everyday life phenomena. Their understanding can even be framed with the math suited to their instruction degree. For quantum physics, however, no table-top experiences are available of microscopic phenomena, even if they are so beautifully explained by quantum mechanics with its advanced formal machinery. Thus, we cannot easily rely on experience nor math to inform our quantum-physics intuition building [9].

One related challenge is that quantum mechanics is counterintuitive and perceived as one of the most bizarre physical theories, involving a change in paradigm perhaps more radical than any other in the history of human thought. As Bohr said, “Anyone who is not shocked by quantum theory has not understood it”. Thus, in school and outreach contexts educators risk providing only conceptual-history storytelling or evanescent tales misled by the use of familiar analogies, which can become a breeding ground for misconceptions. In undergraduate courses, educators risk to provide preeminently formal understanding, ineffective to develop intuition, in fact a roadblock for engagement in the broad student population [10].

Given that we cannot rely on neither experimental or mathematical literacy, nor on everyday intuition, the only one way out seems educating everyone’s intuition in quantum physics by resorting to engaging alternative or complementary forms of experimental and mathematical literacy. More recent discussions focus on the use of the spectacular potential applications of quantum technologies, in particular on quantum computing, as effective means to motivate the introduction of quantum physics concepts and tools [11-18]. This is not surprising, considering that the quantum technologies literature has grown by nearly three orders of magnitude in the last two decades [14], and quantum computing has been receiving increasing attention in view of the possibility of approaching in some future the realm of the so-called quantum advantage [15], i.e. the point where a quantum computer will outperform the most powerful classical computer on a given useful task. Here, we propose that games may provide an avenue to connect quantum technology concepts with concrete user interactions and investigations, and explore the extent to which this idea can be effective.

In games, players are engaged to overcome their limits and rewarded by skill challenges independently of backgrounds and disciplines, what can amplify motivations and unleash creative thinking as everlasting resources for community development [16,17]. Using games as broadly accessible and engaging entry point to complex topics, related educational material can then be developed, scaffolding the build-up of the desired competences.

General engagement and sense of purpose can be amplified in citizen science efforts in which citizens are empowered to actively contribute to the solution of concrete research questions presented in an accessible, often gamified, form [18, 26-28]. According to estimates, by the age of 21 the average US citizen has spent the equivalent of a 40 hours/week full-time job for five years playing videogames [19]. Games are characterized by goals focused on epic and emotion-activating adventures, a set of rules that define constraints but also opportunities to unleash creative thinking that fosters the overcome of skill limits, a feedback reinforcing motivations, a voluntary participation allowing players to leave or keep trying without fearing the consequences of repeated failures. In fact, games are extraordinary tools in pedagogy [20] and competence development [21] and foster community building: a non-perishable and untapped source of extremely valuable goods in terms of problem solving. 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). As one example, citizen science has become a powerful approach in research, educational, and decision-making contexts [16,18]. Even if these ideas might sound extravagant, there are many successful examples of GWAPs for education in classical and quantum physics, including those which tackle research problems [22-26,28] starting from the seminal Foldit experience down to proposals aimed to integrate human and machine minds to solve otherwise intractable quantum problems [26-29]. In the quantum domain, Quantum Game Jams [30] are often used as contexts to conceptualize/develop games, providing ideas, usable prototypes, and educational opportunities in tandem. Quantum games have been proposed also as a context to learn quantum computing without many prerequisites [31] and as an experimental environment for introducing learners to quantum mechanics [32]. It has been noted that allowing scientific experimentation is an important part of fostering scientific inquiry [33], and in the quantum realm, such experimentations are not readily available for the majority of the population. Hence, properly designed games [34] can be used to close this gap to some extent.

We believe that it is timely to dig into this topic in systematic, critical, and rigorous manner to unveil opportunities and criticalities, and elaborate through a theoretical and practical perspective various physics education research tools. This work aims to offer an open-minded inspection of the current status and hereby stemming perspectives, discussing in depth and width the challenge of using quantum games as tools for quantum physics education.

The paper is organized as follows. We start in Sec. 2 by addressing in general the questions of what makes any game ‘quantum' [35] and of how their effectiveness for education can be assessed. In Sec. 3, we illustrate the answer to these questions as provided by the ScienceAtHome research and education group at Aarhus University [36], incorporating the dimension of how humans think about quantum mechanics regardless of their educational level and highlighting potential and practical implications in increasing players' knowledge of quantum research and technology in society. In Sec. 4, we explore the question whether or not there is a lower limit to the age for which one can design effective games for quantum physics education by reporting on the more recent class-workshop experience given by Particle Physics in Primary Schools (PPPS) [37-40] wherein we incorporate arts and crafts and creativity to convey a scientific and inspirational message. Sec. 5 elaborates on the question 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 by illustrating the approach adopted by QPlayLearn [8]. We conclude by discussing in Sec. 6 the methodological and practical challenges that future work in this field should address, before proceeding to a content summary in Sec. 7.

2. What makes a game quantum?

Players interacting with games constructed by classical game engines reinforce their experience of how the classical world operates. A similar approach can be adopted for quantum games to build an intuition about 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 more than 100 ‘quantum games' have been developed around the globe, and most of them are freely accessible [42]. Given the existence of such games, with the increased presence of global online communities (also due to the COVID-19 pandemic), we believe that now is an opportune moment to explore the possibilities provided by utilizing quantum games for education and outreach/engagement purposes within the second quantum revolution. Moreover, developing high-quality quantum games that foster scientific inquiry and raise quantum literacy, could also help in bridging the divide between society and the quantum technologies possibly reshaping our future, which would otherwise enhance inequalities in even more severe manner than the already existing digital divide does [43, 44].

In this context, answers to the following questions emerge to be timely and prerequisites to any further reasoning: (i) what is a quantum game and what makes any game 'quantum'? (ii) can there be a 'quantization method' of classical games, which turns regular games into quantum games? (iii) can we assess the effectiveness of different quantum games with the same assessment tools and, if so, how should these assessment tools be developed? We answer these questions, by referring to the preliminary findings of a summer project organized under the QIntern2021 [46] program put on by QWorld [35].

Here, a *quantum game* is defined as "*a computer (or video) games with one or more of the phenomena from quantum physics embedded in their game mechanics*" [46]. One can also extend this to cover educational (or serious) games directly aiming at introducing quantum mechanics to a wider audience or enable/support teaching of quantum mechanics. However, it might be beneficial in the long run for quantum games to become a concise and self-explanatory concept, the usage of the term should slowly be limited to the one or the other. Educational games can be specifically called as educational quantum games following the definition raised in [39]. Furthermore, games that are capable of running on actual quantum-computation hardware may be accepted as quantum games, since the mere fact that they are able to run might indicate some quantum mechanics is embedded in their game mechanics.

If we consider quantum games within the context of game mechanics, a sort of 'quantization method' can be developed for classical games by introducing or transforming an essential game mechanic to cover a phenomenon from quantum physics (such as superposition, entanglement, non-commutativity, interference, etc.). In this sense, the quantum version of the game will be essentially different from the classical version of the game, which alters the user experience. This can be seen as an initial step towards informal self-learning by players as they learn to work within the new strategic space presented by the 'quantization' of an otherwise familiar game.

Finally, the effectiveness assessment for quantum games is a topic requiring special expertise from the educational research domain. Quantum mechanics is a wide topic, and things get even more complicated as we aim to utilize these games to enable learning, as this, in the long run, can support the development of quantum technologies. Core competencies for quantum technologies are still not fully understood in the literature, and further studies are needed [47,48]. Therefore, developing assessment tools for quantum games contains particular difficulties, and the possibility of assessment tools that can be used for any potential quantum game seems, at the moment, to be highly unlikely.

Following the description of a quantum game above, in the summer of 2021, with a team of interns, 120 quantum games have been collected and classified. Access to the games and relevant documentation can be accessed via Ref. [49]. We mainly collected games from publicly available resources. Of all the games surveyed, 97.5% are free to play, 39% can be played online while 61% requires some sort of download. We identified that only 10% of the games are mobile friendly while almost 90% are for PC or Mac devices. Meanwhile, 23% of the games developed for PC or Mac devices are playable via browsers, indicating that they are also playable on some mobile devices.

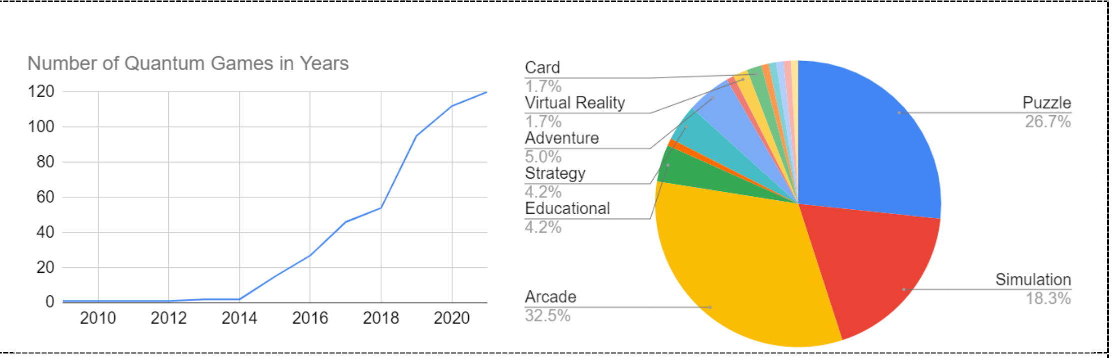

Figure 1. Total number of quantum games in years (left) and their type of classification (right).

In addition to the analyses above, we checked some basic properties related to the games. Firstly, in Fig. 1 it can be clearly seen that development of these games became popular following the first Quantum Game Jam organized in Finland in 2014 [50]. Also, it can be seen that most of the games are of the puzzle, arcade, and simulation types. However, it can also be seen that a wide range of diversification can be observed, which might indicate that quantum game developers are experimenting with game types and mechanics, in search of novelty.
In Fig. 2 we show two properties of these games, (i) whether they have a classical counterpart of the game and (ii) whether or not the game has been developed during a hackathon or a game jam. It can be seen from the figure that most of the games do not have a classical counterpart, which means most developers aimed for creating novel games instead of quantizing existing games. However, 41% of games are quantized, which is not insignificant. Similarly, most of the games were developed during hackathons or game jams, but the ratio of independently developed games (44%) is again not insignificant.

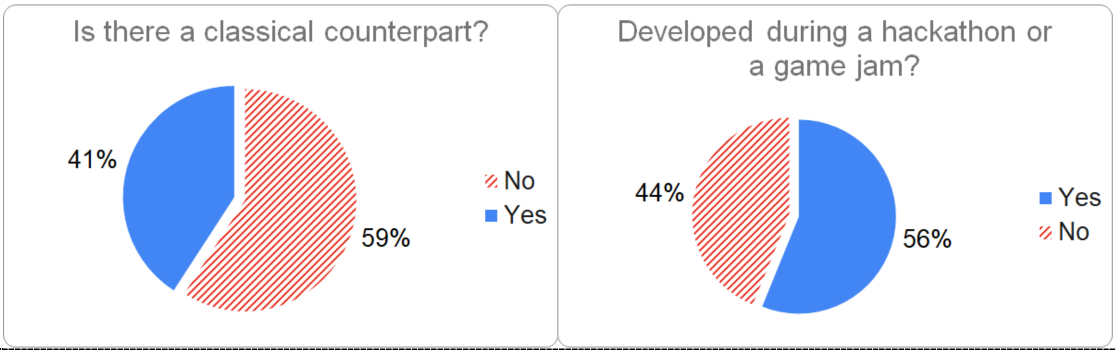

Figure 2. Ratio of games with classical counterparts (left) and developed in hackathon/game jams (right).

3. How do we think about quantum mechanics? The ScienceAtHome case study

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, answers to questions (i)-(iii) outlined in the introduction require prior reasoning on how amateurs and experts approach and solve quantum problems, tapping, in some sense, into human intuition about a very unintuitive subject. In this section, we discuss the answers provided by the suite of quantum games and initiatives developed by ScienceAtHome, a research group at Aarhus University aimed at exploring how humans think about quantum mechanics regardless of their educational level in physics. In addition, ScienceAtHome seeks to educate players on the relevant aspects of quantum mechanics that apply to the games they play. To this end, some of these games include citizen-science-based tasks, where players contribute to cutting-edge quantum research increasing knowledge of quantum research and technology in society, thus building quantum awareness and quantum literacy. All games and surrounding educational material can be found online [55].

3.1. Quantum Moves 2

In *Quantum Moves 2* (QM2, Fig. 3 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. It is found that player solutions can provide valuable information to researchers [28], even in the face of the unintuitive nature of quantum mechanics. For example, Ref. [28] shows that players sample a different part of the control landscape (i.e., the space of all possible solutions to a given problem) than some algorithms. Furthermore, QM2 has been used in numerous educational scenarios, including a randomized control trial on research games in Danish schools [59], where students play QM2 and learn about both classical and quantum physics.

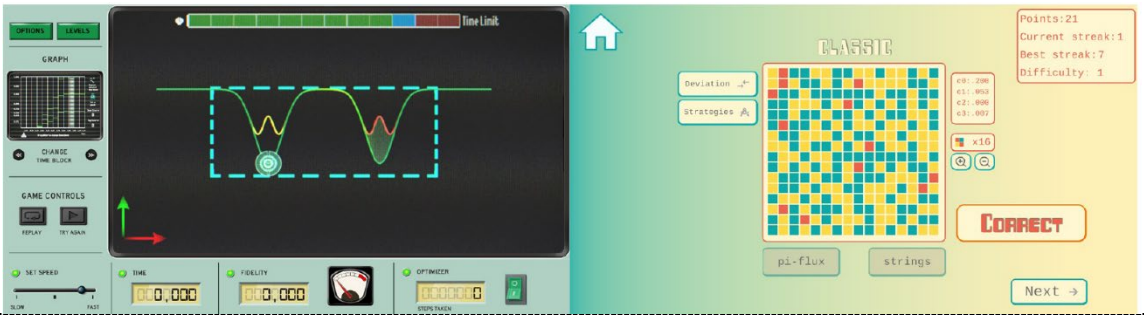

Figure 3. Screenshots of Quantum Moves 2 (left) and the Quantum Mønster (right).

3.2. Quantum Mønster

The *Quantum Mønster* (Fig. 3 right, Danish for "pattern") is being developed to help physicists understand the theories underlying the behaviour of fermionic particles (like electrons) in ordered potentials, which is useful for the study of high-temperature superconductivity, among other things. As with QM2, the *Quantum Mønster* is aimed at understanding how amateurs and experts think about the problem at-hand, with the ultimate goal of helping neural networks to better classify systems that behave according to the different theories of fermion dynamics.

3.3. The Alice challenge

In 2018, the laboratory has been opened up to the general public for the *Alice challenge*, wherein citizen scientists used a gamified interface to optimise the cooling of atom clouds used for quantum simulation experiments. The production of these ultracold atom clouds, which are also a first step towards many quantum sensing and metrology experiments, require a lot of specialized training and equipment to produce. It is found that with an intuitive interface that pared down the required information into an illustration of just what was absolutely necessary, the amateurs were able to make larger clouds than the experimental experts had previously [26]. In general, the experimental methods used to open the lab up to external users required an advanced queueing system [56]. Hopefully, the description in Ref. [56] can guide others who wish to make their experiments remotely accessible to students, researchers, and citizen scientists, as this equity of access can help to bridge the gap between those that can gain first-hand training on advanced quantum experimental systems and those who cannot directly access them.

3.4. Other games

The same idea of understanding how people work with quantum systems rings true in the *Netty* game, a prototype of which can be played at [57]. Here, 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. The *Rydbergator* [58] has also been developed, a gamified tool used for understanding how interacting atoms organize themselves in the presence of highly-excited Rydberg states, which prevent more than one atom from being excited within a certain distance of a highly-excited Rydberg atom.

4. Is there a minimum age? The Particle Physics for Primary Schools project

It is well known that serious games are extraordinary tools conceived in pedagogy since the seminal idea from Montessori that "playing is children's work" [20] to develop their emotional, cognitive, motoric, communicative, relational, and creative thinking [21]. One might then wonder whether games can be used to create forms of quantum physics education in childhood, and down to which age one can dare. In this section, we report on the development of a more recent experience aimed at divulging particle physics research concepts to primary school children [37-40]. Besides the positive results obtained from children feedback, this experience has a methodological significance, as it 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 their later development, including their personal attitude towards science and its perception [41,42]. The project rationale is in the compelling need to modernize the science content of both primary and secondary schools, taking modern 20th-century physics to the classroom, with its fundamental questions, in order to fascinate and inspire wonder in young students, regardless of their socioeconomic or cultural background. 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 they become adults. This message is, however, essential to establish a personal connection between children and science and a sense of ownership of the subject, with the ultimate goal of increasing the society science capital. Science capital can be defined as the sum of all the science-related knowledge, attitudes, experiences and resources that an individual builds up through their life [43].

The project was developed as part of a school activity for primary schools in the UK. 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 teacher training and continuous development so that teachers involved in the project can gain the required scientific literacy needed to teach the relevant concepts to their students. In order to enjoy and profit from the full workshop, the recommended requirement for the student is the ability to read and write at a basic level.

The workshop starts with an introduction to the world of elementary particles, with practical demonstrations of key concepts to promote students ’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 that facilitate the assimilation and consolidation of notions and concepts. The games explore more challenging concepts 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 [44]. The workshop includes both individual and group activities, and concludes with a group activity where children explain and demonstrate 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 Italy. The arts-and-craft aspects of the workshop are crucial to transmit the message that there isn't a rigid dichotomy between art and science, and that creativity is in fact an essential part of the scientific process. Emphasis has been placed on the need to convey a correct and detailed scientific message, albeit one that is 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 (i.e., 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, and these allow students 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 about international science collaborations that are natural in experimental particle physics research.

The aspect of teacher and ambassador 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 (see links in Refs. [37-40]). 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 by collecting feedback from students and teachers before, during and one month after the project. This includes 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 behavior, attitude and perception towards science have been recorded. The results are positive, indicating clear evidence of a positive impact on students. However, work remains to be done to assess whether or not the participants have truly internalised the physical concepts illustrated in the games; this lies outside of the scope of the work presented here.

5. Incorporating quantum games into a global strategic vision: QPlayLearn

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: we cannot root these games and tools (and the interactions they provide) into a durable educational and societal transformation.

In this section, we report on the global strategic vision implemented in QPlayLearn (QPL) [8,45], an online platform conceived to explicitly address challenges and opportunities of massive quantum literacy. QPL was born from a group of scientists passionate about quantum science who firmly believe that everyone can learn about quantum physics and its applications, regardless of their age and background. To this end, QPL develops multimedia tools that aim to enhance the learning process effectiveness, through fun and accessibility, while remaining rooted in scientific rigour. As a strategy for massive cultural change, QPL's mission is to provide multilevel education offering diverse content for different target groups, from primary school, to university students, to quantum science enthusiasts. It is also addressed to companies interested in the emergent quantum industry, journalists, and policymakers needing to grasp what quantum technologies are about.

Inspired by the multiple intelligences theory [60], QPL holistic perspective stems from the recognition that different types of intelligence dominate the learning process of each person. Thus, the platform is conceived to accompany users in their quantum journey via different paths aimed to: (a) build intuition and engagement via games and videos; (b) understand concepts via accessible and scientifically accurate descriptions, graphics, animations and experiments; and (c) acquire formal understanding through the math. Each user can begin from the approach felt easier, and then possibly explore the others. Eventually, it is the combination of the different manners that shifts and expands understanding.

In the Play section, games are used to expose the users to several quantum concepts. In the Discover section, experts explain concepts with short videos, using analogies, experiments or deductive examples. Short animations (*Quantum Pills*) explain concepts at different understanding depths, for experts and amateurs. The Learn section enters the formal core of 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, there is a space dedicated to science-based art projects, where learning proceeds via the preferred user's artistic language, involving creativity at its best: examples are *The Photonic Trail* game [61], combining art, fantasy storytelling and quantum optics elements, and the *Quantum Jungle* [62] (Fig. 4), a 6 m^2 interactive installation in Pisa with 1000 springs and 12000 LEDs, by artist and computer scientist Robin Baumgarten, visualizing the time evolution of a quantum particle.

In this context, games are one of the tools that stimulate users' interactive participation in building intuition about the counterintuitive features of quantum physics. The QPL team has carefully selected games with specific concepts in mind to present to users. The aim is that everyone can approach some of the most relevant quantum properties and phenomena, such as superposition, entanglement, tunnelling, etc., without any technical knowledge being required. The selected quantum games (see Table 1) have been developed by different authors in different contexts, reflecting the variety of quantum games currently available as defined in Sec. 2. In fact, some of them were developed during hackathons or game jams, e.g. *Potatoes Quest* or *Escape: Quantum*, while others have been developed within broader educational projects, e.g. *Psi&Delta* and *Particle in a Box* by the Design and Social Interaction Studio at Georgia Tech University. Note that quantum concepts are used in these games in different ways, from being part of the game mechanics to being presented in an educational context.

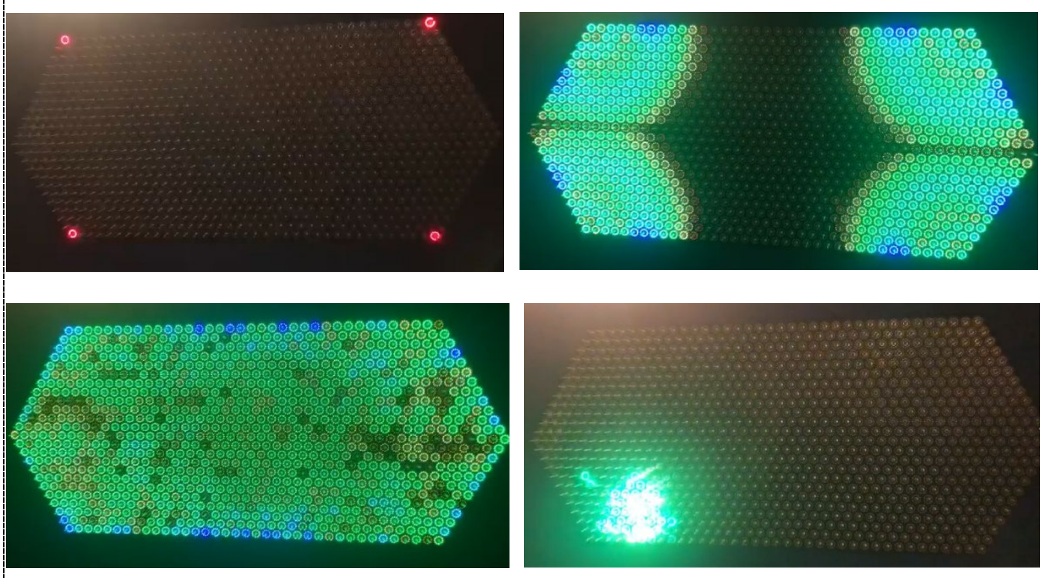

Figure 4. Screenshots from the Quantum Jungle, visualizing the time evolution of one quantum particle. After touching the springs, the quantum particle is created in a superposition state (top left). The probability from computer simulations of the Schrödinger equation evolves according to a quantum walk (top right, bottom left), and is visualized via switching on of LEDs with proportional intensity. Later spring touch is interpreted as a measurement action, visualizing the collapse (bottom right).

Table 1. List of Quantum Games (QG) currently available on the QPlayLearn platform, with thphysical concept each game refers to and the names of the authors.

concept	QG	Authors	Link
Quantum Physics	Particle in a box	Aditya Anupam, Nassim Parvin, Azad Naeemi	https://qplaylearn.com/quest-quantum-physics#section-1
Quantum States	Quantum Playground	Physicists: Guillermo García-Pérez, Sabrina Maniscalco, Laura Piispanen, Matteo Rossi, Boris Sokolov. Dev. MiTale	https://qplaylearn.com/quest-quantum-state#section-1
Qubits	Q|Cards> online	Viktor Minin (Code, Game Design) Sonya Minina (Graphics, Game Design). QPL team	https://qplaylearn.com/quest-qubit#section-1
Superposition	Quantum TiqTaqToe	Evert van Nieuwenburg	https://qplaylearn.com/quest-superposition#section-1
Entanglement	Quantum Solitaire	James Wootton	https://qplaylearn.com/quest-entanglement#section-1
Quantum Meas.	Escape: Quantum	Taryn Allen, Steven Dunn	https://qplaylearn.com/quest-quantum-measurement#section-1
Wave-like Behaviour	Psi & Delta	Aditya Anupam, Nassim Parvin, Azad Naeemi	https://qplaylearn.com/quest-wave-like-behaviour#section-1

Tunneling	Potatoes Quest	Francesco Baldino, Luigina Mazzone	https://qplaylearn.com/quest-tunneling#section-1
Quantum Tech	QWiz	Physicists: Matteo Rossi, Nicola Lo Gullo, Boris Sokolov, Laura Piispanen, Walter Talarico, Sabrina Maniscalco. Dev. MiTale	https://qplaylearn.com/quest-quantum-technologies#section-1

QPL is currently being developed along different directions, including progressive content extension often in collaboration with research groups/institutions, to story-tell their research in quantum science and technology, the development of multiple language versions, and the extension of the class of beneficiaries to 0-99 year old users together with pedagogy experts.

6. Discussion

Games are involved in a wide spectrum of human activities: as natural expression of the human behavior [63], as mathematical expression of human way of thinking [64], as economic behavior. As discussed in depth by the mathematician John von Neumann and economist Oskar Morgenstern in the groundbreaking text creating the interdisciplinary research field of game theory [65], games are connected to human abstraction and formalization: they are an end in itself, engaging, all-encompassing and fun. In fact, the perfect context to allow people to reason in unconventional manners. Playful moments have a significant influence in the development of the comprehension of a subject [66].
Quantum games can make a difference in contexts of limited experimental and mathematical literacy. In fact, a playful moment has a transitional nature between the concreteness of acting and the abstraction ability of thinking irrespective of action. The playful context of the game offers a decontextualization opportunity with respect to school activities. Playful de-finalization motivates and activates personal learning processes via the connection with playful-symbolic skills. The rules of the game, which are required, relate to the affective sphere, become a goal (work), and allow learning [66]. The transition from action to abstraction is an internal process, allowing to develop logical memory and abstract thought. Perception is the spring that pushes us to act for this transition, while the act of playing increases the degree of awareness related to one own's actions, the rules enhancing game attractiveness. Playful activity allows us to experiment by using different mind frames and/or living conditions with no prior conditioning [67]. The player's vision of the world is thus expanded, while "[experiencing] the way of structuring thought towards the universe" [68,69]. Last and not least, games offer access to knowledge tools and to metacognition: it allows players to understand how physics operates.

7. Conclusions and perspectives

In conclusion, we have discussed the significance of using games designed with the purpose of education in quantum physics and technologies and as tools that can complement limited resources of experimental and mathematical literacy, or even substitute them when missing, depending on context and the type of storytelling [70]. We have reviewed the meaning of quantum games and addressed the essential design elements that they should possess, to engage the learner independently of his/her background and the teaching/learning process context, sustaining the experience of thinking about quantum mechanics, and allowing an assessment of effectiveness. We have illustrated one pioneering implementation of this idea, provided by ScienceAtHome, where quantum games are a useful environment for scaffolding both self-reflection and quantum knowledge. This is based on the design of a unique visual interface and means of interacting with a given system, allowing to both tap into what makes human thinking unique and educate the public via their participation in scientific projects. The intrinsic playful nature of games makes them effective independently also of age, and we have also discussed the documented and successful educational path Particle Physics for Primary School, designed to familiarize pupils with the physics of elementary particles. Individual, on-purpose designed tools can certainly empower a teaching/learning process. However, the extent in general depends on the overall strategy where the tools are grafted. Here, we have illustrated the QPlayLearn vision, implemented in a free platform to tailor quantum-science educational processes on the many talents of diverse users, via resources based on multiple languages and symbolic forms. With this flexibility, QPlayLearn can be adopted by educators or outreach experts in diverse contexts, to build up quantum literacy and awareness, and facilitate a diffuse, massive cultural change. We believe this is an authentic priority and, in fact, an unprecedented challenge [71].

The current bottom line about quantum games for quantum physics education naturally leads to further questions. First, although defining quantum games is further explored in the literature [72], a systematic classification is missing of the elements that make a game usefully quantum in relationship to specific educational purposes, and different target audience. Second, a theoretical analysis is needed, to guide the definition of working strategies to use quantum games within a complete teaching/learning process and didactic experiment [73]. Answering these questions is necessarily prior to the design of suited assessment tools. Finally, one truly unconventional challenge concerns the conceivable level depth in *a priori* quantum-game design, to enhance imagination and creativity while efficiently channeling them into operational concept understanding. Exploring this aspect requires a widely interdisciplinary approach, including neuroscience analysis of the visual human mind.

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