Quantum games and interactive tools for quantum technologies outreach and education

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Abstract. We provide an extensive overview of a wide range of quantum games and interactive tools that have been employed by the quantum community in recent years. We present selected tools as described by their developers, including "Hello Quantum, Hello Qiskit, Particle in a Box, Psi and Delta, QPlayLearn, Virtual Lab by Quantum Flytrap, Quantum Odyssey, ScienceAtHome, and the Virtual Quantum Optics Laboratory." In addition, we present events for quantum game development: hackathons, game jams, and semester projects. Furthermore, we discuss the Quantum Technologies Education for Everyone (QUTE4E) pilot project, which illustrates an effective integration of these interactive tools with quantum outreach and education activities. Finally, we aim at providing guidelines for incorporating quantum games and interactive tools in pedagogic materials to make quantum technologies more accessible for a wider

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1 Introduction

The second quantum revolution[1] has been unfolding for over two decades, and numerous countries across the globe acknowledge the potential of these technologies. In the last decade, more than 15 publicly supported national initiatives were launched, with several of them having budgets exceeding billion euros, particularly in the UK,[2] the US,[3] the EU,[4] France,[5] Germany,[6] India,[7] and China.[8] Both the number of new publications per year[9] and the number of patents[10] granted on quantum technologies (QT) have been climbing steadily for the last decade, along with the growing number of start-ups and renowned companies getting into the field. Recently, the field has been receiving attention from private funding sources, which some have been referring to as the 'quantum gold rush.'[11] Within two decades, QT has advanced from a topic that was mainly discussed in physics conferences to becoming a strong contender for a potential future industry.

The developments in QT, similar to most emerging technologies, bring several social and technical challenges. First and foremost, for the general public, QT is still an abstract concept with limited accessible materials on the topic.[12] However, there is an urgency to make QT accessible to lay audiences and facilitate the stakeholders' inclusion into the debate on the subject.[13] Second, the growing advancements in the industry require a rapid expansion of the workforce[14] and an increased level of understanding of QT in educational, business, and policy-making efforts. Finally, similar to most promising emerging technologies, QT is expected to impact society profoundly;[15] however, this may cause preexisting divides on national and international levels to grow wider. These concerns encourage some members of the quantum community to adopt a responsible approach[16] and build a common language.[17]

One of the most important steps taken toward addressing these concerns is increasing public engagement and involvement in QT. The predominant ideas in the existing literature are on increasing quantum literacy at the K-12 and general public[18] levels and focusing more on education and developing transdisciplinary problem-solving skills.[19] Therefore, education and outreach activities are of paramount importance in promoting QT and making it accessible for a wider audience, engaging all potential stakeholders.

The literature on QT and its "social" impact has expanded significantly,[20] and stakeholders' engagement in QT is rapidly increasing; therefore, numerous initiatives are being set forth to address these growing demands. There are several coordinated efforts around the world, such as the QT education coordination and support action for the EU's Quantum Flagship (QTEdu CSA),[21] the Q-12 Education Partnership in the US,[22] and the IEEE Quantum Education[23] initiative. In addition to organizing extracurricular activities, these initiatives also focus on identifying and improving the potential tools that can be utilized by quantum outreach and education practitioners. In this respect, learning quantum concepts through games has gained prominence as an approach to benefit the quantum community at large and support these outreach and education efforts extensively. For example, quantum games are a key means of engaging students and teachers, making up four out of five of the Q-12 Education Partnership's QuanTime K-12 classroom activities.[24] The quantum games are used here to refer to computer (or video) games with one or more of the phenomena from quantum physics embedded in their game mechanics —note that this is not (in principle) related to research efforts extending game theory to include quantum mechanics.[25,26]

The development of science-based games can set out to achieve a variety of goals, including for educational purposes, citizen-science-based[27] research purposes, science outreach and public engagement, and/or fun. Games are unique among other tools for research and education in that,

if they are widely adopted, they have the potential to reach audiences beyond most coordination efforts, and thus they can be useful vectors for increasing quantum awareness. This is important for two reasons. First, it is beneficial that the goal of understanding the science targets not only current and future technical experts on the topic but also people with other occupations and skills who will transform the science into technologies impacting many other areas. Equally important is the learner gaining exposure to a new concept, thereby making the concept less intimidating when reencountered. This is especially impactful to learners from underrepresented or disadvantaged backgrounds who have less opportunities or encouragement to experience this topic in the first place, helping them to succeed in the field utilizing their skills and perspectives.

In this article, we introduce a wide range of tools that have been tested by developers and used by the community for several years. We present different approaches and tools, together with the experiences of their developers, aiming to provide current and future practitioners of quantum outreach and education activities a better understanding of their application and extent. Most of the authors are members of the pilot project *Quantum Technologies Education for Everyone*[28] (QUTE4E) organized under the Quantum Technology Education Coordination and Support Action (QTEdu CSA) of the EU's Quantum Flagship program. Therefore, the list of games and interactive tools provided here consists of a non-exhaustive but representative list. Further information on the pilot project can be found in Sec. 5.

The article is formatted in the following manner. In Sec. 2, we argue for the importance of photonics in QT outreach and education efforts. In Sec. 3, we discuss the relationship between science-based games and quantum games,[29] including a brief discussion on the evaluation of quantum games. In Sec. 4, Secs. 4.1–4.7 are dedicated to introducing quantum games and interactive tools for QT outreach and education, and in Sec. 4.8 we explore some activities in creating quantum games. Finally, in Sec. 5, a more detailed description of the pilot project QUTE4E is given.
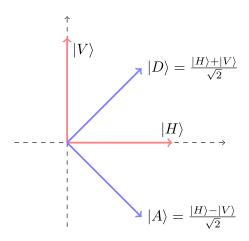
2 Locating Photonics in QT Outreach and Education

To understand QT—such as quantum cryptography, quantum computing, or quantum sensing—a knowledge of the quantum phenomena that they rely on is essential. These relevant quantum concepts include superposition, entanglement, interference, dynamical evolution, and measurement,[30–33] and there is an emerging literature introducing these through optics concepts.[34–38]

Using qubits allows us to discuss quantum information without relating it to physics.[39] Although this adds simplicity in some respects, it also results in challenges. First, all current quantum devices are deeply rooted in physics. For now, to use them efficiently, we need to consider which operations are physically possible. Second, quite a few phenomena are easier to explain with concrete systems. This offers a direct way to visualize them and relate them to the broader fields of wave physics, electrodynamics, and optical communications.

Introductions that aim to be entry-level usually use electron spin[40] or photon polarization[41] to introduce quantum mechanics. Arguably[42] photon polarization is an easier two-level system that translates to demonstrable experiments with classical light and behaves more intuitively with rotations and superposition.

Quantum mechanics is known to be prone to misconceptions, resulting from otherwise well-intentioned physicists, teachers, and science communicators.[43] Misconceptions are common even among students of physics.[44,45] A common problem with teaching quantum mechanics lies in training students to distinguish the phase of a superposition. Telling someone that it is possible to have a qubit in the $|0\rangle$ and $|1\rangle$ state simultaneously leaves no such space and fails to distinguish between statistical uncertainty and quantum mechanics, as explained by Scott Aaronson.[46]

> *Over the years, I've developed what I call the Minus-Sign Test, a reliable way to rate popularizations of quantum mechanics. To pass the Minus-Sign Test, all a popularization needs to do is mention the minus signs: i.e., interference between positive and negative amplitudes, the defining feature of quantum mechanics, the thing that makes it different from classical probability theory, the reason why we can't say Schrödinger's cat is "really either dead or alive," and we simply don't know which one, the reason why the entangled particles can't have just agreed in advance that one would spin up and the other would spin down.*

Fig. 1 Polarization of light offers a straightforward way to present orthogonal states. With a typical mapping $|H\rangle = |0\rangle$ and $|V\rangle = |1\rangle$, quantum states $(|0\rangle \pm |1\rangle)/\sqrt{2}$ have a direct physical representation, both easily demonstrable experimentally in a class and matching the high-school definition of orthogonality.

However, photon polarization gives a quick way to distinguish such states and to show that they are orthogonal (see Fig. 1).

Moreover, such systems give an easy way to explain measurements (with linear polarization filters known in photography and LCD screens, followed by detectors known from cameras), translate back and forth with nonlocal superposition over different paths (via polarizing beam splitters), and relate to simpler and laboratory-demonstrable experiments with interference. In addition, several quantum communication protocols were first demonstrated with photons. These include quantum key distribution with BB84[47] and Ekert[48] protocols, the Bell inequality violation,[49,50] and boson sampling.[51]

Photonic systems can be easily extended to more advanced systems. For example, to encode qudits (quantum systems with d levels, typically $d > 2$), one uses different spatial modes and angular momentum, giving rise to qualitatively different classes of entanglement than that achievable with qubits.[52] Photonics can also be used to simulate molecular vibrations and dynamics.[53]

At the same time, it is crucial to underline that there are many other physical implementations of quantum technologies—involving spin, energy levels, and currents in superconducting loops, among others. We believe that, to teach modern quantum technologies, we need to show phenomena from different angles—both physical and abstract. The same core properties of quantum mechanics are important regardless of which system we study, yet some may be better to explain a given phenomenon or more easily relatable to currently available quantum devices and protocols. Hence, we present a wide array of quantum games and quantum interactive tools, each approaching from various angles, underlying various phenomena.

It should also be noted that there is an emerging literature on introducing quantum technologies (especially quantum computation) through computer science,[54–56] programming[57–60] oriented, and visually oriented (no-math) approaches[19,61–63] in parallel to the physics-focused approaches. All of these can be thought of as efforts in further developing the outreach and education landscape of quantum technologies.

3 Quantum Games and Interactive Tools as Novel Methods for QT Outreach and Education

We believe that learning the basic concepts of quantum physics and quantum information science should be made accessible to the public regardless of background to understand the significance of the second quantum revolution,[13] and anyone regardless of their background can access the tools to learn and develop quantum technologies. A number of resources are available,[64] but understanding requires that the learning be sequential:[65] quantum computing and algorithms

need prior understanding of qubits, quantum gates, and so on. Games are a natural way for pacing the progression through which learners may grasp these concepts. Efforts are needed to establish dissemination channels to reach a broader audience, and games can serve the purpose with their popularity across society.

The interdisciplinary nature of QTs leads to a diverse range of skills that the quantum workforce should possess;[14] thus it should include people from different backgrounds. This poses a particular challenge: teaching quantum mechanics is daunting to teachers for whom this is also a new topic. Virtual labs and learning tools, accompanied by explanations of the simulated physics, are cost-effective environments for exploring and building intuition of quantum phenomena.

The connection between interactive storytelling and quantum computing was briefly explored in the literature.[66] However, a comprehensive discussion on why and how these tools can be utilized for education and outreach purposes has not been made. We provide the groundwork for such a discussion by providing a quick introduction to science-based (Sec. 3.2) and serious (Sec. 4) games, followed by a description of quantum games and interactive tools from their developers (Secs. 4.1–4.7).

In this section, we cover four topics. We discuss in Sec. 3.1 early and current quantum tools, the former being precursors of today's quantum games and interactive tools. In Sec. 3.2, we briefly discuss the wider arena of science-based games, with its increase in number and success being a valuable witness of the general trend and an inspiration. Section 3.3 illustrates explorable explanations as an example of how enhanced interactivity can play a practical role in science communication. Finally, in Sec. 3.4, we discuss the challenge of evaluating quantum games, providing suggestions for necessary future work.
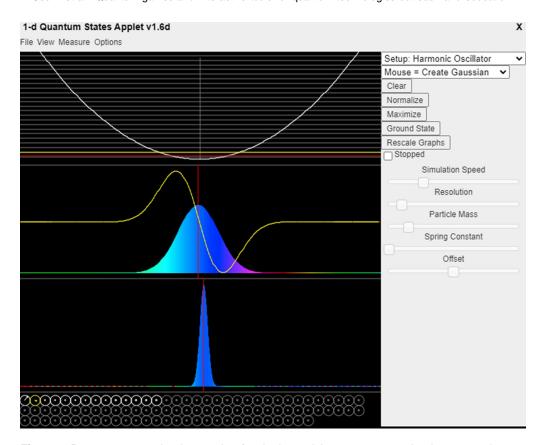
3.1 Interactive Tools

A number of different computer-based quantum tools have been developed for educational purposes. Typically, these tools are geared toward the visualization of quantum phenomena. Early efforts by the Consortium for Upper Level Physics Software released quantum visualization software packages in the mid-1990s;[67,68] some of the authors of these software packages also released a book on quantum mechanics simulation.[67] Later efforts included a series of books by Thaller[69,70] and Zollman et al.[71]

In the early 2000s, Paul Falstad released a series of Java applets simulating physics,[72] including 12 on quantum mechanics and many others on waves physics. In particular, the one-dimensional quantum mechanics applet allows one to draw any potential and any wavefunction, as well as explore the position space, momentum space, energies, and eigenstates simultaneously (Fig. 2). The ripple tank applet allows for the exploration of interference—crucial for both classical wave physics and quantum phenomena. Unlike other simulations, a user can draw the interference setup in a sandbox mode. Paul Falstad's applets gained enough popularity to be ported as mobile apps and rewritten in JavaScript to be usable with modern browsers.

Other web-based applications include the Physlet simulations[74] and a set of simulations developed by Joffre.[75] The ubiquitous PhET simulations[76] have developed a set of quantum-specific simulations; PhET researchers have published a wide array of research on the design and use of their simulation.[77–80] Other such research-validated quantum simulation tools include the QuILTs[81] developed at the University of Pittsburgh,[82] the QuViS tutorials[83] developed at St. Andrew's University,[84,85] and the Quantum Composer simulation tool[86] developed at Aarhus University,[87,88] which is described in more detail later in this paper.

With the exception of the node-based programming in Quantum Composer, the tools developed here are typically set modules exploring a specific quantum phenomenon (sometimes including supplementary material that instructors can use to develop exercises), and interactive tools (e.g., the PhET, QuViS, and QuILT simulations) allow students to easily modify parameters and explore the simulation in more detail. However, none of these tools can be classified as games as they lack the required elements in the interface and design that engage the students outside their traditional educational goals. In Sec. 4, we explore more recent and ongoing efforts in accomplishing this task, but first, we introduce the concept of science-based games and explorable explanations as an example.

Fig. 2 1-D quantum mechanics applet (a single-particle quantum mechanics states in one dimension) by Paul Falstad.[73] An early simulation gives a user the ability to simultaneously see (and edit): 1-D potential, eigenstates with eigenenergies, wavefunction as a function of position and time, wavefunction as a function of momentum, and relative amplitudes of each eigenstate.

3.2 Science-Based Games

The traditional way of teaching includes textbooks, lectures, and projects. This teaching method is performed top-down, with clear instructions and expectations. Students are tested via grading of projects, homework assignments, and exams. Usually fun, or the ability to explore on one's own, is not the key focus. Often students' motivation is extrinsic—to pass a course with a good grade. These activities can be gamified, provided with supplementary goals, scores, and challenges to make them more engaging.

In contrast, science-based games[29] approach teaching from the opposite direction: to primarily focus on creating an experience sparking intrinsic motivation,[89] that is, students play for fun, but learn in the process, as their gaming experience requires learning concepts to proceed or provides an explorative pathway through the game that promotes learning[90] (even if it is not strictly necessary).

There are several existing games showing different aspects of physics—special relativity theory,[91] electromagnetism,[92] classical physics, and orbital mechanics.[93] There are games that teach computing—creating circuits from the simplest blocks—NAND gates[94] and low-level programming in assembly. Although a lot of games are standalone one-off projects, some game developers specialize in science-based games, e.g., Zachtronics (algorithmics) and Test Tube Games (physics). Some science-based games go way beyond the niche – SpaceChem and Kerbal Space Program sold over 1 million and over 2 million copies on Steam,[95] respectively.

3.3 Explorable Explanations

Explorable explanations[96] (or "explorables") come at educational games from the opposite direction: instead of "games, but with science communication added," they are "science

$$X_k = \frac{1}{N} \sum_{n=0}^{N-1} x_n e^{i2\pi k \frac{n}{N}}$$

To find the energy at a particular frequency, spin your signal around a circle at that frequency, and average a bunch of points along that path.

Fig. 3 A self-descriptive formula of the discrete Fourier transform: a web-based MathJax implementation[99] of an equation color-coding scheme designed by Stuart Riffle from 2011.[100] Earlier approaches of color-coding go back to the Byrne's Euclid from 1847[101] subtitled "In which Coloured Diagrams and Symbols are Used Instead of Letters for the Greater Ease of Learners."

communication, but with interactivity added," although we should note that interactivity is a necessary but not sufficient condition for something to be considered a game. Most explorables are educational articles, with embedded simulations instead of static media such as images and videos. The term "explorable explanation" was coined in 2011 by interaction designer Bret Victor,[97] with an ambitious goal of creating a two-way communication between the author and the reader. With an open-ended creative environment, readers can challenge the author's assumptions by going beyond what the author ever imagined. This ambition is explained more in the 2019 essay[98] by former Khan Academy designer Andy Matuschak and quantum physicist Michael Nielsen. These approaches are tightly related to exploring new visual languages of communication (see Fig. 3).

Deep learning shares many similar concepts with QT—both hyped, fast-growing technologies, are heavily based on linear algebra with tensor products and have a nontrivial entry barrier. The abundance of online tools that help users to learn and directly use deep learning already gets traction in gaming[102] and can provide guidance on how to present quantum technologies in an accessible, ready-to-use way. There are already numerous explorable explanations in machine learning and AI,[103] including general introductions to probability and statistics,[104] decision trees and validation in machine learning,[105] training of artificial neural network classifiers,[106] and interpretability of convolutional neural networks.[107,108] In 2016 to 2021, a dedicated peer-reviewed journal *Distill* aimed at providing interactive explanations of novel research.[109]

Although the interactive environment of Jupyter Notebooks is a standard way of providing introductions to quantum software frameworks,[110,111] there is only a handful of other quantum explorable explanations, e.g., a spaced-repetition-based introduction to quantum computing,[112] an introduction to quantum Fourier transform,[113] and an exploration of single-qubit gates.[114]

3.4 *Evaluation of Quantum Games*

A common question when considering any tool is whether it truly works as intended, and quantum games are no exceptions. Currently, neither common design methodology[115] nor universal evaluation tools for quantum games are available. This is largely due to fragmented game-development processes[116] (i.e., by professionals, by university researchers, or in hackathons) and the diverse game goals (i.e., research, education, outreach, and/or fun). Indeed, some of the games described in Sec. 4 have been evaluated individually. For example, the developers of Quantum Moves 2, with its focus on citizen science, published their results in a peer-reviewed journal.[117] Similarly, the games Particle in a Box[61] and the Quantum Odyssey[118] have articles published in peer-reviewed journals containing evaluation sections. However, a proper and comprehensive evaluation and assessment scheme that can be applied to a variety of quantum games is missing in the literature. Validation of these quantum games, especially when ensuring that educational games serve to teach students relevant concepts, is important and should be further developed as activities in the field are progressing. Although the development and discussion of a universal quantum game evaluation tool is beyond the scope of this paper, we offer some suggestions here.

First, we need to categorize quantum games in terms of their basic information such as on which platform they run and their licenses, their types, and the concepts that they are drawing upon. Efforts to do this are underway,[116] but the task difficulty grows with the impressive growth

rate of the quantum games landscape and with the rate at which games become obsolete because of, e.g., operating-system compatibility and security or operating system development leading to the acquisition of game-breaking bugs. We believe that it could be useful to develop a quantum games version of Physport,[119] which is a repository of research-based recommendations, assessments, tools, and practices for physics education, where games can be rated. For example, the Force Concept Inventory[120] received a gold star rating from Physport for its extensive research-based evaluation.

In parallel, researchers should work to develop best practices for the evaluation of quantum games (similar to those developed for quantum software[121]), focusing on the common goals of research, education, and fun; these best practices can be collected in the same repository as the games themselves. Also, within the repository, we can denote whether the game is being actively developed, is in a usable state, or has been deprecated in some way. This can be an invaluable tool for tracking how quantum games, their goals, and their use cases change over time.

Evaluating the effectiveness and efficiency of a video game for education requires a number of steps,[122] which as a pilot we are completing. To start with, we need to work out a storytelling format, in which the use of the purpose of the quantum game or interactive tool is made explicit. This has been the subject of theoretical work introducing the concept of culture-scientific storytelling with special attention to quantum science and technologies,[123] which is being tested in outreach events such as the workshops devoted to high-school students around the Quantum Jungle interactive installation.[122] Then, suitable evaluation tools must be designed in correspondence with on-purpose didactic experiments. For example, in one such experiment performed in a high school in Treviso (Italy), the Quantum TiqTaqToe video game was used as a central tool in a highly compact didactic intervention lasting just two afternoons (including a TiqTaqToe tournament) to educate students on the concepts of quantum state and measurement, quantum superposition, and entanglement.[124] Suitable evaluation tools in the form of questionnaires were designed for this purpose and analyzed; they showed a high degree of effectiveness of the quantum game in supporting the students' ability to develop an operational understanding of the aforementioned concepts.[124] Although much systematic research needs to be performed along similar directions, these first steps appear quite promising and encouraging.

A preliminary effort to categorize the games presented in our paper is provided in Table 1.

Table 1 A summary of games presented in Sec. 4.

Title	Initial release	Platform	License	Type	Key concept(s)
Alice Challenge	2017	Web	Proprietary, free	Citizen science game	Ultracold atoms, experimental optimization
Hello Qiskit/Hello Quantum	2018	Web/iOS/Android	Apache (web), proprietary, free (mobile)	Puzzle game	Quantum gates
Particle in a Box	2016	Web/MacOS/Windows	Proprietary, free	Single player platformer game	Superposition, energy levels
Psi and Delta	2018	Web/MacOS/Windows	Proprietary, free	Multiplayer platformer game	Superposition, energy levels, color-energy relationship
Quantum Game with Photons	2014	Web	MIT	Puzzle game	Photons
Quantum Odyssey	2020	Windows	Proprietary, paid	Puzzle game	Quantum circuits
Quantum Moves 2	2018	Web	Proprietary, free	Citizen science game	Ultracold atoms, optimal control, wavefunctions, and transport
Virtual Lab by Quantum Flytrap	2019	Web	Proprietary, free	Simulator/puzzle game	Photons, quantum information, measurement

Finally, these different approaches introduced above can be supported by a criteria-based assessment, utilized by the quantum games hackathon juries organized by the Quantum AI Foundation to assess the submissions. These criteria are listed as correctness, playability, originality, and completeness for that particular hackathon (further information on the hackathon is provided in the Sec. 4.8.1):

- Correctness: Are the assumptions and usage of quantum mechanics and quantum computing appropriate?
- Playability: Is the game entertaining? Does it have educational potential? Is the user interface inviting?
- Originality: How creative and innovative is the idea?
- Quality and completeness: Is the game polished and ready to play? Are the mechanics well introduced?

To sum up, we are in the early stages of quantum games being accepted as a concept of their own, instead of just games designed to teach quantum physics. Therefore, development of evaluation tools and practices should also be considered to be an important research direction.

4 Experiences from the Field of Quantum Games and Interactive Tools Development

Computer-based games have evolved from a niche pleasure for a select few to a worldwide phenomenon that is now a part of the everyday lives of millions of people. Games have surpassed movies and television shows as a cultural, sociological, and economic force to be reckoned with. Games represent a new, robust economic sector that has amassed significant money, technological know-how, and skill for many nations. Games User Research[125] has become an essential aspect of game production, and many of the industry's most notable companies now adopt this methodology. This translates to higher product quality, tremendous financial success, and a more positive work atmosphere, in which employees can see evidence that their efforts are making a difference.

Serious games,[126] an umbrella term encompassing games having additional aims beyond entertainment, are extensively employed in various fields, including healthcare, telerehabilitation, military, and education. Serious games have always focused on the physiological and spatial consequences of the games on the participants.[127] Serious games and game technologies have been utilized for simulation and training in various areas, and these technologies have been adapted to computer, virtual reality (VR), and mixed reality (MR) settings. Milgram et al.[128] offered a precise method for differentiating between various realities, and MR has been characterized as "mixed virtuality and augmented reality," as well as "any combination of real-world and virtual-world features." The application of gaming technology in VR and MR has enhanced spatial task research while also allowing for immersion, presence, and usability studies.

The use of games and serious games has been a recent and powerful tool for experimenting with new quantum algorithms, providing new communication protocols, and teaching quantum theory to the masses. Recent advancements in implementing and testing quantum games have been an ongoing effort. In the rest of this section, we provide a selection of such games described by their developers.

4.1 *Hello Quantum/Hello Qiskit*

The IBM Quantum Composer was released in 2016 and provides a simple and graphical way to write quantum circuits and run them on prototype quantum computers. This service was (and is) available for free to the general public, allowing them unprecedented access to quantum computer hardware.[129] However, without the knowledge of what quantum circuits are or how quantum gates work, there was still a significant barrier to entry.

The Hello Quantum project, a collaboration between IBM Research and the University of Basel, was intended to alleviate this issue. The idea was to visualize quantum states and the effects of gates, so people could gain an intuitive understanding of simple quantum circuits.
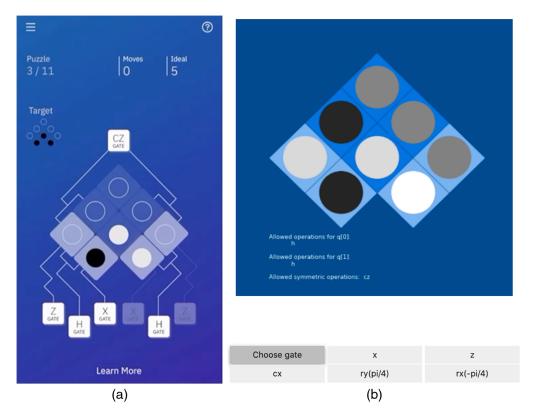
Fig. 4 (a) Screenshot of the Hello Quantum app and (b) a Jupyter widget-based puzzle from the Hello Qiskit section of the Qiskit textbook.

This interactive and visual method for learning was presented as a puzzle game, with the player being challenged to find the circuit that would take an input state to a desired output state.

The resulting products were released in four stages:

- A simple ASCII prototype, used in lectures at the University of Basel in 2017;
- The app Hello Quantum, released on iOS and Android in 2018[130] (Fig. 4);
- The section Hello Qiskit, released in 2019 as part of the interactive Qiskit textbook[131];
- The section "Visualizing Entanglement," released in 2021 as part of the interactive Qiskit introduction course.

In each case, the learning material was presented by providing interactive puzzles, intended to build intuition and provide context, as well as text providing an explanation of how aspects of the game relate to quantum computing.

For "Hello Quantum," the puzzles and text were delivered entirely separately. The idea was that the player could play through the puzzles as a short and informal game. Then, once they had mastered the game mechanic, interested players could go on to read about how their new in-game skills translate to quantum computation. This text was not limited to the app itself, but instead represented the inaugural posts of the Qiskit blog. These posts were entitled "Visualizing bits and qubits,"[132] which explained the visualization used in the app, and "Getting started with the IBM Q Experience,"[133] which explained how to transfer the learned skills into what is now called the IBM Quantum Composer.

It was expected that the readers would be led to the former blog post by the app and to the latter by a link in the former. However, view statistics show that only around 1% of views for the former can be traced to following the in-app link. Instead, the majority (around 58%) came from search engines. For the latter post, 81% of views come from sources external to the blog, such as 40% through email, instant message (IM), and direct and around 27% from search engines.

Given these results, we can conclude that the blog posts were a more successful learning resource than the app. This is because every app user who went on to fully understand the game

will have followed the link to the app, but these app users are only a small percentage of the total readership.

For the "Hello Qiskit" section of the Qiskit textbook, the puzzles were implemented within an interactive Jupyter notebook. This was located in a chapter specifically for interactive demos. An analysis of views for the textbook was conducted for the period March to November, 2020.[60] It was found that the view share of this section is very comparable to those of the first two chapters. In fact, the average number of views for sections in chapters 1 and 2 during the period is very similar to the number of views for the "Hello Qiskit" section. During this time, 71% of views for the chapter come from within the textbook. These statistics suggest that it serves an integrated role as part of the introductory materials within the textbook. This motivated the more prominent usage of the visualization in the "Visualizing Entanglement" section of the new interactive Qiskit introduction course.

These results demonstrate an additional benefit to the design of quantum games and interactive tools. By finding visual and interactive representations of the mathematics behind quantum computing, we make it easier to describe. This allows us to create more engaging and understandable explanations in text. It is therefore worth considering making fully blog-based companions to any educational quantum game or interactive tool.

It is worth noting briefly that a similar insight was gained from the game Battleships with partial NOT gates. This was one of the first games to use a quantum computer and was designed primarily so that the source code could be explained in a blog post.[134] There is therefore little evidence of it being played, but the blog post remains the most viewed on the Qiskit blog by some margin.

4.2 *Particle in a Box/Psi and Delta*

"Particle in a Box" and "Psi and Delta" are digital games designed to support high school and undergraduate students in learning introductory quantum physics. The games were designed and developed as part of an interdisciplinary team of electrical engineers, media scholars, and HCI researchers comprised of undergraduate and graduate students as well as faculty at Georgia Tech. "Particle in a Box" aims to support learning quantum physics by allowing students to virtually explore, compare, and experiment with worlds that follow the laws of classical and quantum physics.[61–63,135] Building upon Particle in a Box, Psi and Delta aims to teach quantum physics through collaborative inquiry by requiring two players to cooperate, develop, and employ concepts of quantum mechanics together to resolve challenges involving quantum physics.[136] Both games can be downloaded and played at Ref. 137.

Both games integrate quantum physics into the game mechanics using a concept map of the infinite square well. For example, to reify the concept of light color affecting energy levels, Particle in a Box requires students to find and collect light bulbs of the appropriate color and bring them to a lamp to shine light onto an electron. Similarly, to promote engagement with the relationship between "area under the curve" (the curve referring to the probability distribution of the electron) and the probability of the electron, Psi and Delta uses platforms with different widths and measurement counters that count how many times an electron is measured under each platform to express probability. The concept map of the square well problem used by both games is provided in Fig. 5.

4.2.1 *Particle in a Box*

Particle in a Box is a 2-D single-player platformer game built in Unity in which the player plays the game through a virtual avatar who travels through a 2-D rendition of the classical and quantum worlds. The classical world, set in a lab-like environment, (Fig. 6) involves challenges based on Newtonian physics such as jumping over a ball and increasing its total energy. After playing the classical world, players shrink down to the quantum world (Fig. 7) which is based on the infinite square well problem. It involves an electron that is trapped in a 1-D quantum wire and exhibits quantum behavior such as superposition and energy quantization. The challenges here are based on understanding introductory quantum physics. Experiencing both worlds affords
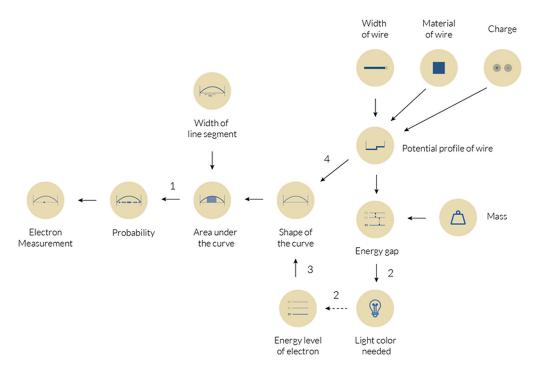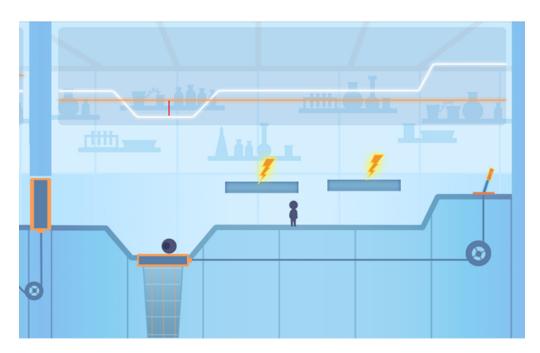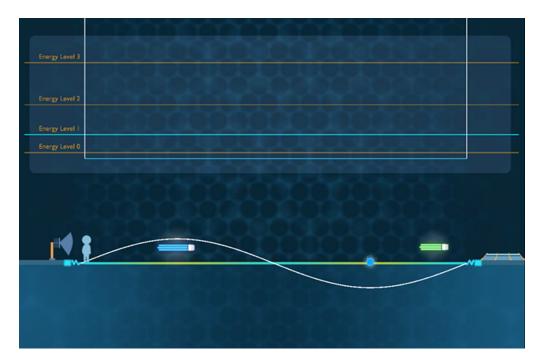
Fig. 5 The Concept Map of the square well problem.

Fig. 6 The classical world in Particle in a Box. The player must reach the energy bolts, carry them, and place them in the path of the moving ball.

students the opportunity to compare their similarities and differences—an approach that has shown to be effective in learning quantum physics.

Both worlds have similar objectives: to raise a particle's energy. In the classical world (Fig. 6), the objective is to raise the energy of a rolling ball so that it pushes a lever located higher up, which opens the door to the next level. In the quantum world (Fig. 7), the objective is to increase an electron's energy up 3 levels by gathering light bulbs of the correct color and shining light on the electron's quantum wire. Having similar objectives enables direct

Fig. 7 The quantum world in Particle in a Box. The player must carry the colored bulbs to the lamp (left) that will shine light and increase the electron's energy level (top). The blue dot is the electron, and the bright line it is on is the wire. The curved white line illustrates the wavefunction of the electron.

comparison between concepts such as position and energy, which manifest differently in classical and quantum physics.
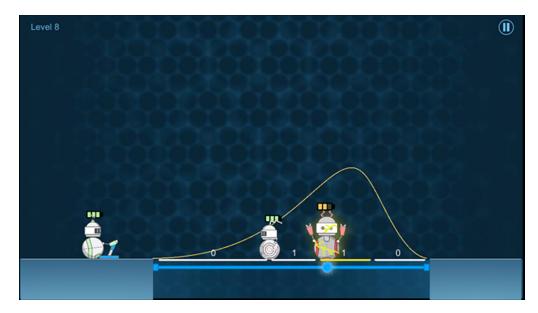
Further, in both worlds, if the player hits the particle, they faint and must restart. In the classical world, this means coming into contact with the ball. In the quantum world, this means coming into contact with the measurement of an electron particle. The electron by default is in a state of superposition. However, it is also measured regularly and "appears" each time as a particle. The position where this electron particle appears is random but follows a probability distribution (curved white line in Fig. 6). Through repeated measurements, the game simulates an "experience" of probability as the player learns to identify the locations where the electron is likely to be measured and therefore where they are more likely to be hit. Because players faint if they are hit by the particle in either world, they must learn to carefully analyze the behavior of those particles in both worlds, thereby promoting further comparison.

Particle in a Box was evaluated with undergraduate electrical engineering students at Georgia Tech and showed an improvement in students' conceptual understanding of probability.[61] Students further reported an increase in comfort level with the key concepts taught in the game. The game was awarded the Student's Choice Award at the Serious Games Showcase and Challenge in 2015.

4.2.2 Psi and Delta

Psi and Delta builds on our findings of Particle in a Box by students adopting the role of two robots, with the aim of defeating opposing robots in a world governed by the laws of quantum mechanics. Students accomplish this task using concepts of quantum mechanics to lure and "shock" the opposing bot. If a student's bot touches the opposing bot or gets "shocked," it loses part of its health. If any player's bot loses all of their health, the level restarts.

The game is divided into two parts. In part one, the students develop models of the concepts of superposition and probability (Fig. 8). As discussed earlier, when an electron is confined in a small area, it will enter a superposition state, i.e., it will exist in multiple positions simultaneously. To break this superposition, one needs to take a "measurement." In the game, the electron is confined to a small blue quantum wire. In contrast to the automatic measurements, in Particle

Fig. 8 Taking a measurement in Psi and Delta. One player (left) takes the measurement by pulling a lever, while the other (middle) lures the enemy bot to a higher probability area. Here, the enemy bot is shocked by the measured electron as it stands on a platform under which the electron was measured.
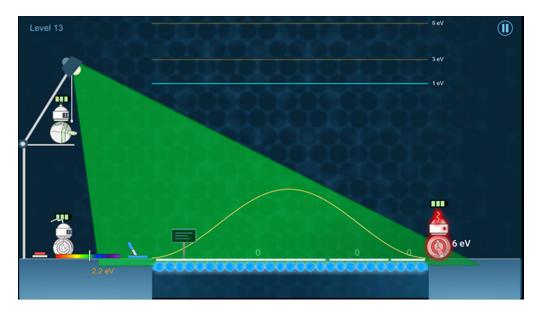
in a Box, it is the players who take measurements by pulling a lever. Each time a player pulls the lever, a measurement is taken, which collapses the electron from its superpositions state to an unpredictable position on the wire for a brief moment. Any robot (player or enemy) standing on a platform directly above the collapsed electron will get "shocked" and lose some health (see Fig. 8). The position where the electron collapses is probabilistic, i.e., some positions are more likely than others. The relative probability of these positions is illustrated by the electron's probability distribution, the orange curve in Fig. 8. The longer the platform is and the higher the curve above it is, the more likely the electron will be measured under it. After each measurement, the electron returns to superposition.

In part two, students develop models of energy levels (Fig. 9). Here, the opposing bot has a shield that protects it from getting shocked. To break the shield, the electron needs more energy. Electrons can only have a discrete amount of energy such as 1 eV (electron-volt) or 3 eV in the case shown in Fig. 9, but nothing in between. Energy can be supplied to an electron in the form of light, which consists of discrete energy packets (photons) with energy that depends on their color. To excite an electron from a lower energy (say 1 eV) to a higher energy (3 eV), one must shine photons with the exact energy as the gap (2 eV). In the game, students can shine light using a lamp and change its color using a spectrum.

This collaborative inquiry approach encourages students to share their ideas and work together to understand basic quantum physics concepts.[136] Qualitative evaluations of Psi and Delta with undergraduate physics and astronomy students showed that it was effective at engaging them with the basic concepts of quantum physics and had potential to be integrated more formally into traditional lectures.[18] The game was also presented at the Smithsonian Creativity and Innovation Festival held at the National Museum of American History in Washington DC.

4.3 *QPlayLearn*

QPlayLearn[138] is an online platform conceived to explicitly address, within a global strategic vision, the challenges and opportunities of widespread quantum literacy. QPlayLearn was born from a group of scientists passionate 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

Fig. 9 Shining light to increase the electron's energy level in Psi and Delta. The horizontal lines on top indicate the electron's energy levels. The spectrum (bottom-left) lets players change the color of the light shined.

background. To this aim, interactive tools enhance the learning process effectiveness, fun, and accessibility, while remaining grounded with scientific rigor. As a strategy for cultural change in a wide range of social strata, QPlayLearn offers diversified content for different target groups, from primary school 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.

Inspired by the theory of multiple intelligences,[139] 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 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; and (3) acquiring formal understanding through mathematics. Such a three-step method is used in Quest, the QPlayLearn quantum dictionary, in which each entry is composed of various sections exploiting different kinds of learning-approaches and resources. For each concept in the dictionary, each user can begin from the approach that feels easier to them and then possibly explore the others. Eventually, it is the combination of the different pathways that shifts and expands the understanding of quantum physics and technologies.

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. In addition to games, short animations (Quantum Pills) explain concepts at different depths of understanding, which is useful for experts and nonexperts. In the Discover section, specialists explain concepts with short videos, using metaphors, experiments, or deductive examples. 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 also a space dedicated to art and science projects, as art can help bring people closer to science and quantum technology in a way that goes beyond academic learning or scientific popularization.

Because of the foundational concept, QPlayLearn is aimed at wide and diverse (free) use, to tailor education processes on quantum science on the many aptitudes of different users, operate a diffuse and massive cultural change, and build up literacy and awareness. Because of this flexibility, QPlayLearn can be incorporated by educators in a widespread context. The effectiveness of the QPlayLearn approach needs to be assessed by means of physics education research tools in on-purpose designed experiments. Meanwhile, a number of developments are underway;

these include completing the quest environments, adding a multiple language version, and extending the class of beneficiaries to 0 to 99 years old users, together with pedagogy experts. In fact, the latter represents an authentic priority and an unprecedented challenge.[18]

4.4 *Virtual Lab by Quantum Flytrap*

Quantum Flytrap is a company founded in 2019 that is focused on bringing quantum technologies closer to users by developing user-friendly graphical interfaces. In addition to on-going commercial projects involving developing a no-code Integrated Development Environment (IDE) for quantum hardware, Quantum Flytrap provides educational tools to demonstrate capabilities of interfaces and real-time simulations.

Virtual Lab by Quantum Flytrap (2019)[140] is a real-time online simulation of an optical table, supporting up to three entangled photons. The Lab uses a drag-and-drop interface for positioning optical elements, such as photon sources, mirrors, polarizing and nonpolarizing beam splitters, and Faraday rotators. The inspiration comes from ease of use and capabilities of construction systems, such as LEGO Bricks, the Goldberg machine video game The Incredible Machine,[141] and grid-based games such as Chromatron and Minecraft. Most elements have configurable parameters such as phase shift (for reflections, delays, and wave plates), polarization rotation (for Faraday rotators and sugar solutions), and absorption rate. The Lab supports both destructive measurements and nondemolition POVM measurements.

Virtual Lab is a successor to Quantum Game with Photons (2016),[142] an open-source puzzle game with 34 levels and a sandbox. Quantum Game with Photons simulates a single photon and its polarization. Although most setups could be understood within the framework of classical wave optics, the binary character of photon detection shows a few quantum phenomena. For example, the game demonstrates the Elitzur–Vaidman bomb tester—an experiment in which the quantum measurement plays a crucial role.

The original Quantum Game with Photons had over 100k gameplays and was cited in seven peer-reviewed publications by unrelated researchers.[18,143–148] It was selected as the top pick in gamifying quantum theory in *The Quantum Times*.[149] Based on in-person and email feedback, we learned that it was possible to solve a large fraction of levels without prior exposure to quantum physics, e.g., for high school and undergraduate students. At the same time, a few levels provided a challenge to PhD students and established quantum optics professors.

Virtual Lab is focused on reinventing the interface, design, and numerical performance. Our simulation supports multiparticle quantum physics. Unlike most other simulations, it goes beyond qubits. Virtual Lab simulates pure quantum states with photon polarization, four cardinal directions, and a discrete position of a photon on a grid. Consequently, for a typical grid size, a single photon requires around 1000-dimensional vector space, so a three-photon simulation requires a billion dimensions. Therefore, Quantum Flytrap needed to develop a custom high-performance sparse array simulation in the low-level programming language Rust—as none of the off-the-shelf solutions were suitable.

Virtual Lab offers a set of example experimental setups demonstrating key experiments in quantum measurement, quantum cryptography, quantum communication, and quantum computing. Example setups involve single photon experiments, such as nonorthogonal state discrimination, the Elizur–Vaidman bomb tester, the BB84 quantum key distribution protocol, and the concept of nondemolition measurement affecting interference. The two-particle setups include the Ekert quantum key distribution protocol, the Deutsch–Jozsa algorithm, and the CHSH Bell inequality violation. With three particles, we can demonstrate quantum teleportation and Greenberger–Horne–Zeilinger correlation (Fig. 10).

The measurement results can be subject to logical operations (such as AND or XOR), used to alter other elements (e.g., to perform quantum teleportation), treated as a goal (for puzzles and course assignments), correlated (for Bell inequality violation), or saved as a CSV table for arbitrary processing.

Moreover, a laser mode allows us to explore classical wave phenomena, such as the three-polarizer paradox (generalizing to the quantum Zeno effect), interferometers (Mach–Zehnder, Michelson–Morley, Sagnac), optical activity, and magneto optic effect (with applications such as an optical diode).

Fig. 10 A three-particle Greenberger–Horne–Zeilinger entangled state, visualized simultaneously as (A) waves on the board, (B) entanglement between particles, and (C) the quantum state, in bra-ket form.

Virtual Lab provides multiple ways to investigate an experiment, its outcomes, and the current quantum state. The multiverse tree feature allows users to explore the whole experiment, including all possible measurement scenarios. In the Copenhagen interpretation, all branches are related to probabilistic outcomes. Within the Everettian many-world interpretation, each branch is a coexisting part of the quantum state, representing worlds that are unlikely to interfere with each other.

In each time step, it is possible to explore the exact state (ket) with a preferred choice of the basis and coordinates of complex numbers. Furthermore, we visualize entanglement of every particle with the system.

Virtual Lab has been used for quantum information courses at Stanford University and the University of Oxford, as well as by Qubit for Qubit's Introduction to Quantum Computing online course. Virtual Lab features over 450 custom, user-created setups. It has around 70 users on a regular working day and peaks at over 700 during events.
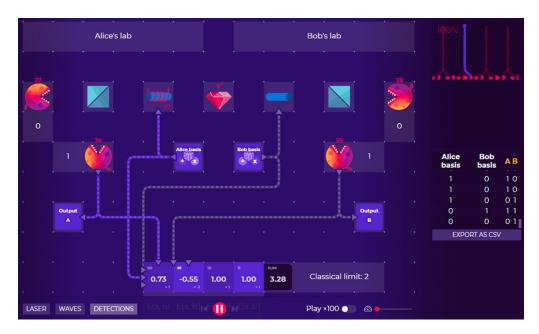
Quantum Flytrap released Quantum Tensors[150] is an open-source JavaScript library for in-browser quantum information processing. It goes beyond qubits and supports physical multi-particle physical systems (polarization of light and spin), as well as qudits. It allows for the creation of states, changing bases, performing unitary operations, measurements (destructive and nondemolition POVMs), and entanglement entropy. It has sparse linear algebra operations (including with tensor products) and support for quantum circuits.

Virtual Lab allows for exploration of quantum states at each single time step (see Fig. 11) and matrices for unitary operation and projections (see Fig. 12). Quantum Flytrap open-sourced BraKetVue (or $\langle \varphi | \psi \rangle$.vue)[151] is a visualization of quantum states and operations in the popular web-development framework Vue.js. It allows for the creation of interactive quantum explorable explanations (e.g., in a blog post with an introduction to quantum gates[114]) and can be used in other web-based environments, such as presentations with Reveal.js (created in RISE in Jupyter Notebook or with R Markdown).

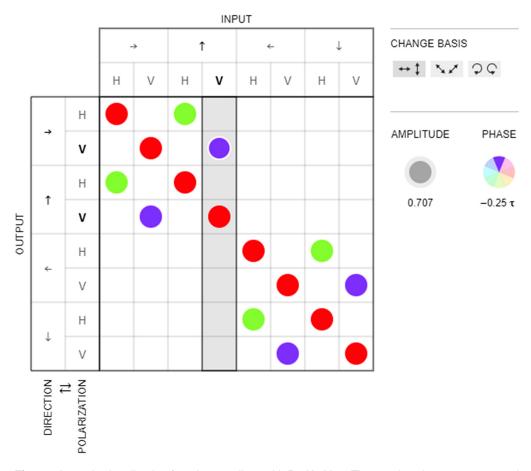Matrix visualizations allow us to show the magnitude and phase of transition in a visual way, dynamically change the basis, and explore the tensor structure (e.g., change the order of particles).

4.5 Quantum Odyssey

Quantum Odyssey is a privately funded, large software project, still in development by Quarks Interactive,[152] but the alpha version is already available for the public. Currently, the software

Fig. 11 An experimental setup for the CHSH Bell Inequality violation. Note that the experiment depends on two random variables (Alice's and Bob's basis), provides a table of all measurements (downloadable as a CSV file), and presents all correlation in real time.

Fig. 12 A matrix visualization for a beamsplitter with BraKetVue. The matrix values are presented with a circle size (radius for the amplitude, area for the probability) and color (hue for the phase). Index labels incorporate the tensor structure.

Fig. 13 Images 2, 3, and 4 are snapshots of the evolution of a quantum state vector in visual form for two particles that start in the ground state 00 and reach the Bell state 00 and 11. The balls at the bottom show the desired output solution, and the user is required to place a Hadamard gate to achieve it as shown in 1.

comes with over 20 h of fully narrated, self-paced education ranging from quantum optics phenomena to coding quantum algorithms. The software also contains a vast encyclopedia that verbosely explains key quantum mechanics concepts. People working on the software have various backgrounds (researchers in education, quantum physicists, artists, and game developers).

Behind Quantum Odyssey is the concept of quantum literacy, as coined by Nita et al.[19] The aim of Quantum Odyssey is to make quantum physics and computing knowledge accessible to all audiences, regardless of their background, by making learning about and working with quantum algorithms exciting and fun. Quantum Odyssey is a fully visual and software-assisted method for learning how to create new and optimize quantum algorithms for quantum computers. Equivalent to everything that can be achieved using the gate model framework, users can design quantum algorithms for any purpose (ranging from designing physical interactions in optics to more advanced quantum computing algorithms) without requiring any background knowledge in STEM. Quantum Odyssey shows in real time the dynamics of the quantum state vector, including its evolution as the user adds quantum gates to build quantum algorithms (Fig. 13).
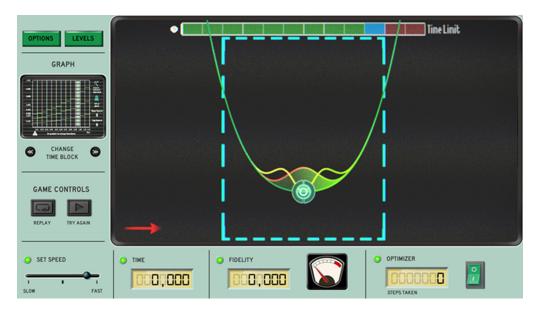
The software was tested in schools and found to be suitable for teaching quantum physics and computing from the age of 12 and above. The results of the research study[118] show that the Quantum Odyssey visual methods are efficient in portraying counter-intuitive quantum computational logic in a visual and interactive form. This enabled untrained participants to quickly grasp difficult concepts in an intuitive way and solve problems that are traditionally given today in master's level courses in a mathematical form. The results also show an increased interest in quantum physics after play, with a higher openness and curiosity to learn the mathematics behind computing on quantum systems. Participants developed a visual, rather than mathematical, intuition that enabled them to understand and correctly answer entry level technical quantum information questions. Another interesting find is that the design of the visuals of the software makes it equally appealing to both female and male participants, that is, both genders were found to be equally able to solve complex mathematical problems if they were given in a visual puzzle form within Quantum Odyssey.

In future releases, the following new features will be introduced:

- The ability to import/ export visual puzzles to IBM Qiskit and run algorithms right on an IBM QCPU. Everything designed with Quantum Odyssey is fully compatible with Qiskit.
- Multiplayer, collaborative efforts in optimizing and discovering new quantum algorithms.
- Community puzzle publishing and ranking system for puzzle creators and puzzle solvers.

4.6 *ScienceAtHome*

ScienceAtHome[153] was founded in 2011 at Aarhus University with the goal of developing gamified tools to enable citizen scientists to participate in cutting-edge quantum research.

Fig. 14 The Quantum Moves 2 interface, showing the *Shake Up* level. The goal is to move the potential (green line) left and right within the cyan dashed box to excite the quantum fluid (green shaded curve with red-yellow outline) from its initial, ground state (as shown) to the final, first excited state (yellow outline). This must be done within a certain amount of time, and the goal is to achieve the highest overlap (fidelity) between the final state and the yellow-outlined state. For more information, see Ref. 117.
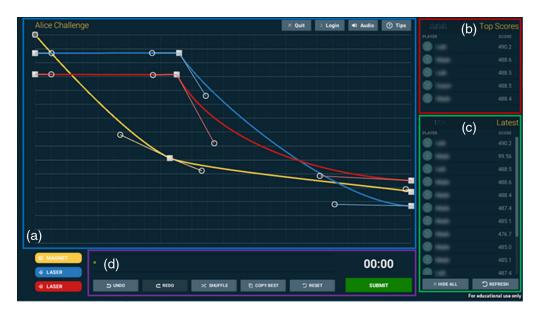
Today, ScienceAtHome boasts a suite of games and tools for education and citizen science in a variety of academic fields.

ScienceAtHome's flagship game is Quantum Moves 2[154] (Fig. 14), a game in which citizen scientists can play through a variety of scenarios, including three scientific problems relevant to cutting-edge research in quantum technologies. To date, at least 250,000 players have played Quantum Moves 2. Research has shown that player-generated solutions could have some advantages over random seeding when applied to optimization of the scientific problems, even when the solution landscapes of these problems are complex.[117] In particular, players explore the solution landscape more efficiently and can capture solution strategies that algorithms may miss. This is not to say that players are better than algorithms, but rather that the insights of citizen scientists can be useful when deciding how to solve a given quantum problem.
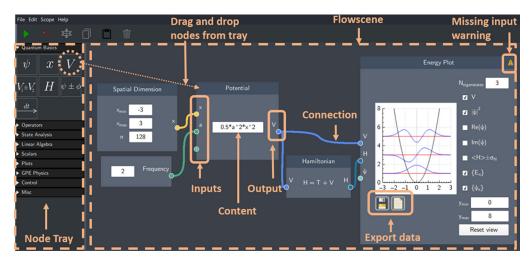
In 2017, researchers at ScienceAtHome opened up their quantum laboratory to the general public in the Alice Challenge.[155] The goal of the Alice Challenge was for users to optimize the number of rubidium-87 atoms in a Bose-Einstein condensate, or BEC,[156,157] a cloud of extremely cold atoms that can then be used for a variety of quantum technology experiments. We found that citizens operating the experiment remotely[158] were able to create larger BECs than the local experimental experts,[159] a difference that we attribute largely to interfacing and gameplay (Fig. 15), that is, we built a simple and intuitive interface that allowed citizens to collaborate (in that any player could copy a previous solution and modify it) to solve the problem-at-hand; such intuitive interfacing is key to success when considering citizen science projects, quantum or otherwise.

ScienceAtHome has also developed a number of educational tools, including the Quantum Composer,[86] which is built on the QEngine C++ library;[160] both tools are freely available for download and use. The QEngine is a research tool for the simulation and control of 1-D quantum mechanics,[161] and the Quantum Composer wraps the functionality of the QEngine into a flow-based tool for quantum visualization. Thus, the Quantum Composer (Fig. 16) is aimed at introducing students to quantum mechanics and quantum research via a modular interface that can be used to simulate a wide range of problems in introductory and advanced quantum mechanics, including those that are not analytically tractable.[87,88]

ScienceAtHome researchers and educators have used these tools in a number of educational and outreach settings, including the aforementioned week-long Alice Challenge in 2017 in

Fig. 15 The interface for the Alice Challenge, showing (a) the spline curves that the users could manipulate to control the time-dependent laser powers and magnetic field coil currents that controlled the final BEC atom number, (b) a top score list, (c) a list of the latest submissions and their scores, and (d) a control toolbar, including the estimated wait time. Players could take any other player's solution [as shown in (b) and (c)] and modify it. Figure reproduced from Ref. 158.

Fig. 16 The Quantum Composer interface. Users can drag-and-drop nodes (representing space, the potential, a plot, etc.) from the left-hand tray into the simulation space (called a flowscene). Connections are then made between the nodes to direct information from one node to another. This figure shows how one can set up a simulation that shows the first three eigenenergies and eigenstates of the quantum harmonic oscillator. Figure reproduced from Ref. 87.

which 600 citizen scientists around the world took part. Quantum Moves 2 featured heavily in the 2018 ReGAME cup,[162] with more than 2000 students from 200 high school classes around Denmark playing a set of citizen science games as they worked through educational content that scaffolded the games, and the planned Project FiF[163] (Forskningsspil i Folkeskolen, or research games in high schools) will expand this to 150 schools around Denmark. Quantum Composer has also been widely used as a part of ScienceAtHome outreach efforts in Denmark and around Europe, including a 3-year-long outreach training effort coordinated as a part of the quantum sensing and control (QuSCo[164]) Marie Skłodowska-Curie interactive training network.[165] The outreach training program was aimed at teaching PhD students to communicate their research via

a variety of methods, including videos, blog posts, and the development of inquiry-based learning sessions.

4.7 *Virtual Quantum Optics Laboratory*

The Virtual Quantum Optics Laboratory (VQOL) is a graphical web-based software tool for designing and simulating quantum optics experiments[166,167] developed by the Applied Research Laboratories at the University of Texas at Austin. The VQOL was developed initially as an educational tool for introducing high school and early college students to quantum information science, but it has also proven to be useful as a research tool for analyzing real-world experiments.[168] The graphical interface presents a top-down view of a notional optics table with a menu of components that can be placed and configured as desired. To aid visualization, six base colors are used to represent polarization and interpolate these across the Poincaré sphere (see Fig. 17). A variety of components are available; these include passive linear optics (waveplates, polarizers, beam splitters, etc.), light sources (LEDs, lasers, and Gaussian entangled states), and measuring devices (power meters and detectors).

In an educational setting, VQOL may be used to introduce optics concepts (either classical or quantum) or to explore quantum phenomena and applications. Over the past 2 years, we have used VQOL as part of a full-year high school course on quantum computing[169] as well as part of a two-semester introduction to quantum computing for university freshmen and sophomores. A typical introduction to qubits begins with the concept of polarization, which can easily be understood in terms of transverse waves on a string. We then introduce projective measurements through an initial investigation of Malus's law using a laser, polarizer, and power meter. We transition to the Born rule by introducing a neutral density filter, which attenuates the laser light to the single-photon regime, and replacing the power meter with a detector for photon counting. Students perform guided experiments and explore the phenomena before drawing inferences to uncover the physical laws behind them. Upon this foundation of physical intuition, a more concise abstract mathematical description may then be introduced. One important aspect of these experiments is that students are challenged to consider appropriate data analysis methods for conceptually connecting "counts" with probabilities. Because, from an experimental point of view, there is not a well-defined number of "trials," this exercise raises interesting interpretive

Fig. 17 Screen shot of the VQOL interface showing a delayed-choice experiment. A laser (left) produces horizontally polarized light (red) that is attenuated by a neutral density filter before entering a Mach–Zehnder interferometer. The random polarizations (multiple colors) are due to vacuum noise. The upper arm has a half-wave plate (blue disk) that can provide which-way information by changing the polarization to vertical (blue). The two detectors have polarizers (green disks) to detect horizontal light.

questions. Students must consider how to normalize their data and account for dark counts, just as they would need to do in a physical optics lab.

Beyond introducing elementary concepts, we have also used VQOL for deeper explorations into quantum physics. Over the past 2 years, we have offered a virtual experimental quantum optics program to our university students. The program aims to connect theory to experiment by exploring quantum information science in an experimental optics setting. Students work in groups of two to four individuals and are tasked with exploring about 10 different experiments over a 9-week period. Students select which experiments to investigate and are given only general guidance on the goals and phenomena to be explored. At the end of each week, the groups get together to present and discuss their findings. Possible experiments include quantum state tomography, an optical implementation of Deutsch's algorithm, delayed choice and quantum eraser experiments, quantum teleportation, entanglement swapping, and violations of Bell's inequality.[166] We have found through post-program surveys that students generally respond well to the open-ended nature of the experiments and feel that it gives them a more authentic research experience than traditional, more structured undergraduate laboratories.

4.8 Activities in Creating Quantum Games

The first recorded hackathon was organized by developers of the OpenBSD[170] software in June 1999, and the term was coined by its organizers. It is commonly used to refer to "a usually competitive event in which people work in groups on software or hardware projects, with the goal of creating a functioning product by the end of the event."[171] The first (or the zeroth depending on the perspective) game jam was organized by The Indie Game Jam community in March 2002.[172] It usually refers to a more relaxed and noncompetitive event compared to a hackathon, similar to a jam session of a musical band. The created games can have educational or research value.[173] Moreover, a game jam can foster creativity, learning, and collaboration of the game developers to explore technologies and develop skillsets.[174] Since their emergence, both terms have been adopted by software communities and beyond, and the number of hackathons and jams have grown to hundreds per year.[175] Therefore, their adoption by the community of quantum game developers was not a surprise. Some further readings on game jams can be found here.[176–180]

The first quantum game jam was organized in Finland in 2014 as a part of the Finnish Game Jam,[181] and the first quantum hackathon (not focused on games) was organized in April 2018 by Rigetti,[182] where two quantum games were also developed. Following these, several quantum game jams[183] and hackathons focused on game development were organized. Reference 183 describes the organization of five quantum game jams and rates for each the quantum game developed based on how enjoyable and informative on quantum concepts that it was.

In what follows, we provide a recent example of a quantum games hackathon organized in September 2021. This is followed by the description of a quantum computer games project-based course at the University of Texas at Austin, organized by the developers of the previously introduced Virtual Quantum Optics Laboratory tool. Both examples are described by their organizers in detail, to be used as templates by any interested readers.

4.8.1 Quantum Games Hackathon by Quantum AI Foundation

The Quantum Games Hackathon[184] was an online event organized in 2021 by the Quantum AI Foundation (QAIF)[185] in collaboration with members of QPoland,[186] a QCousins branch of QWorld.[187] The event was related to the Warsaw Quantum Computing Group meetups.[188] The main motivation of this hackathon was to popularize and foster innovation in quantum computing as well as to provide the participants with an opportunity to develop quantum programming skills. The hackathon started with two days of introductory talks and workshops (September 25 and 26, 2021) followed by a week for project development. The submission deadline, as well as the announcement of the winners, was the third of October 2021. In addition, QAIF and QPoland organized a separate workshop prior to the hackathon based on QWorld's Bronze[189] material to give participants more time to learn necessary skills.

The invitation to the event was shared on social media platforms: Facebook, LinkedIn groups, and Twitter. There were 128 registrants from 41 countries. The participants worked in teams composed of up to five people, formed during a match-making event. Participants were advised to have team members with expertise in different domains, e.g., quantum programming, user experience design, business development, computer games development, etc. Communication within teams, with mentors, and with the organizers was held using the hackathon Discord server. In addition to the quantum computing workshop, participants had an opportunity to listen to lectures given by experienced researchers, developers, and entrepreneurs working in the quantum computing domain. The talks, given over 2 days at the beginning of the hackathon, included introductions to software and programming platforms (Qiskit and the JavaScript environment), existing games (e.g., Quantum Odyssey), and interface design and accessibility in games. All lectures were given using Zoom; most of them were recorded and are available on QAIF's YouTube channel.[190]

At the end of the event, seven solutions were submitted. According to the hackathon rules, the participants were requested to submit a link to a public GitHub repository containing the quantum game code and a short video presentation (up to 5 min). All submissions were assessed by a jury composed of six members according to the following criteria:

- **Correctness:** Are the assumptions and usage of quantum mechanics and quantum computing appropriate?
- **Playability:** Is the game entertaining? Does it have educational potential? Is the user interface inviting?
- **Originality:** How creative and innovative is the idea?
- **Quality and completeness:** Is the game polished and ready to play? Are the mechanics well introduced?

The three best projects were awarded prizes; there was also an additional prize funded by *Quantum Flytrap* for the best game developed using *JavaScript*. All other prizes were awarded by the other Strategic Partners of the hackathon: Snarto, Cogit, Quantumz.io, and KP Lab. The winning solutions were:

- **DaveTheHackerman_ZXgame**,[191] a game on diagrammatic ZX-calculus.[192]
- **QuanTetrum**,[193] a Tetris-inspired game that uses three important concepts of quantum physics: superposition, entanglement, and measurement.
- **QG_Crusher**,[194] a Candy Crusher-like game with quantum gates.
- **Quaze**,[195] a quantum maze in which each maze tile is a gate changing the state of a quantum particle.

4.8.2 Quantum computer games project-based course at the University of Texas at Austin

For the mid-semester project in the Quantum Computing stream of UT Austin's Freshman Research Initiative (FRI) seven groups of one to three students were tasked with programming their own games to run on quantum computers. In a short lesson introducing the concept of quantum games, we briefly covered motivations for designing games including showing off or testing state-of-the-art hardware, engaging participants for the purposes of education and entertainment, and, importantly, as a creative exploration of new technologies. For the purposes of the project, we defined a game as something with a goal, rules, and feedback. The player uses the rules to attempt to accomplish the goal; feedback is received and, depending on the particular game, may be used to modify the player's strategy. To avoid overly contaminating the students' creativity, we added only that each game must contain four essential quantum effects: superposition, interference, entanglement, and measurement. All of these quantum features must be present for the player to manipulate and/or experience.

When designing quantum computer games, students must consider each of the four required quantum effects from a creative perspective rather than simply in an academic context. Using Qiskit, our class builds many of the popular quantum algorithms including Deutsch-Jozsa, Grover search, phase estimation, and factoring; though our teaching style tends to be exploratory,

we eventually lay out the algorithms in easy-to-follow steps. The students must understand the steps to apply them in a computer program and analyze the results. In this game-making project, the students do not have concrete steps to follow. Instead, they must either fit quantum effects into a pre-existing game or build original rules around the desired quantum effect. This takes comprehension of quantum concepts as a prerequisite and pushes the student beyond simple understanding into experimentation and imagination.

Each group submitted their programmed game along with a written report highlighting the quantum aspects of their game, potential strategies, and any other interesting features. They also each gave a brief (5 to 7 min) presentation and gameplay demonstration. The game titles and short descriptions are included below.

- **Qhess:** Chess in which each piece can move in superposition. At each turn, all of the potential states of a piece must be considered when moving that piece. Measurement occurs when pieces interact by occupying the same square.
- **Quantum Mafia:** A quantum version of the party game, Mafia. Each villager chooses a decimal number as their phase. The mafia member uses quantum phase estimation to attempt to kill the villager. The mafia RSA encrypts their identity, and the detective uses Shor's algorithm to attempt to discover them. The doctor uses the Deutsch–Jozsa algorithm to attempt to save targeted villagers.
- **Quantum Boss Battle:** You must battle a boss monster whose health is represented by a random entangled circuit. In each turn, you attack the monster by applying quantum gates. Your goal is to reduce the state to all 0s. A measurement of 1 or the time running out will result in Game Over.
- **Battle of Millenniums:** The Deutsch–Jozsa algorithm run on a function of your username determines whether you fight for the Angels or the Devils. You have three attacks of varying strength in superposition with a healing action. You also may use a magic attack if you have the magic points available. Your goal is to reduce the enemy to zero health, but damaging the enemy also gives them magic points. Bonuses are awarded according to the outcomes of Grover's algorithm and arithmetic operations in quantum Fourier space.
- **Quantum Uno:** A quantum version of the popular card game, Uno. Each card is implemented as an oracle for Grover's algorithm. Superposition cards take the place of Wilds, Entanglement cards act as a sort of delayed Skip, and a whole new Add Phase card rotates the state of the deck.
- **Quantum FPS:** This is a first-person shooter style game in which health is given by the computational basis representation of a 3-qubit state. Hadamard and CNOT gates act as ranged attacks, and X gate is a close-range attack. You can change your own state using H or CNOT on yourself. You can measure yourself or your enemy, but you die if your state is ever measured as $|000\rangle$.
- **Quantum Invasion:** Player 0 and Player 1 compete for territory across a neutral zone that starts in superposition. Each player has a number of actions to spend on different attacks such as rotating a single qubit, rotating multiple qubits, and entangling target qubits in superposition. At the end of the game, the state of the board is measured, and the player with more qubits in their state wins.

5 Pilot Project QUTE4E

Storytelling in quantum outreach is crucial given the unintuitive nature of quantum mechanics and extremely timely for the potential effect that quantum technologies may have on future society. Counterintuitive examples of quantum phenomena provide engaging platforms to practice the process of scientific thinking with the general public using experimental, creative, and formal literacies. QT also allows educators to integrate Responsible Research and Innovation (RRI) dimensions into a given outreach activity.

The pilot project Quantum Technologies Education for Everyone (QUTE4E) was conceived to respond to the above challenges by building tools to address and measure what aspects of QT outreach and education should possess to be efficient and effective.

The key concept of QUTE4E is that engagement is a fundamental requirement of education, regardless of the learner's technical skills, age, or socioeconomic background. Thus, the goal of the pilot is to design basic and engaging storytelling of the essential concepts in a captivating and language-accessible manner to educate intuition and boost creativity for every target audience: public, students, educators, school and academic teachers, outreach experts, QT companies, or policymakers. Building on this basic conceptual map, the pilot is developing formal language tools with increasing levels of complexity and technical content according to the audience's degree of formal education or educator training.

In the following, we describe how these challenges are addressed by the pilot efforts, via an example on the storytelling of light. Light is a transversal concept in physics, and its concepts are taught in subfields of physics ranging from quantum mechanics to cosmology. The story of light and photonics provides a means to engage with a broad audience as it can be tuned from basic concepts, such as an explanation of how rainbows are formed and why the sky is blue, to specialized technical fields such as quantum optics that directly impact quantum technologies. In addition, because light is familiar to everyone, describing some of its intriguing properties can also encourage curiosity regarding what is behind the concept of light and how to apply it in our daily life, fostering an interest in science and its applications.

Thus, we believe that teaching through storytelling is the right tool to ignite passion and bring excitement and engagement about nature, and, more specifically, the world of quantum technologies. This method allows the audience to take an active role in searching for the explanation for a previously misunderstood observation, exercising scientific thinking, and exploring new forms of literacy.

In addition, this approach is particularly applicable to gamified and interactive activities that support the active role of the learner in a natural way by introducing relevant concepts through increasingly difficult challenges and levels, creating natural environments for visualization and player experimentation, and providing feelings of success that can foster increased motivation for further education in quantum physics and technology.

The QUTE4E group is designing a general format for storytelling in quantum science and technology that makes full use of the process of scientific thinking.[183] This format starts from observation to create understanding and is then formalized and finally benchmarked back into fact-checking. In this process, the experimental and formal literacies that are required to perform the different steps are built using interactive tools such as those described in this work. Examples include virtual experimental labs and quantum games, popular science animations, and artistic immersive experiences. Once the functional scientific thinking process is scaffolded, one may ask whether engagement is generated through the storytelling of basic quantum science and technologies. In fact, our answer to this question runs along two different dimensions: an educational consideration and a RRI analysis.

Finally, we strongly believe that our storytelling should be guided by and articulated within the RRI dimensions, i.e., public engagement, open access, governance, gender equality, ethics, and science education. The QUTE4E group is developing outreach concepts with a strong focus and involvement of the stakeholder groups to identify the current needs and to respond with innovative solutions.

The pilot resources are conceived to be dynamically updated from existing ones. A nonexhaustive list of existing resources developed by the participants to the pilot consortium includes the following: quantum games with a purpose of education (as in ScienceAtHome, QPlayLearn), also developed in Quantum Games Jams and Hackathons, quantum physics labs (e.g., Quantum Composer, Virtual Lab by Quantum Flytrap, 3D space, Labster[196]), quantum concepts labs (Quantum Composer), quantum algorithms labs (IBM Quantum tools/ Qiskit, Quantum Odyssey), quantum computing resources (IBM Quantum/ Qiskit), educational tangible objects for K12 experience activities (Trump cards at Birmingham[197,198]), quantum pills and animations (QPlayLearn, Quantum Tour[199]), artistic (visual, audible, and touchable) immersive experiences (e.g., Quantum Garden, Quantum Jungle[200,201]), and online courses for different types of beneficiaries (QWorld, QPlayLearn, IBM Quantum/Qiskit). A selection of these was discussed in Sec. 4.

Within the bounds of the pilot, a special emphasis is planned on developing methods of extending the "reach" of a given initiative. Many (already existing) resources lack the proper

channels and means to disseminate and be used widely by their potential beneficiaries. As the pilot develops its tools, it can also develop/improve means of reaching target audiences, looking for strategies aimed at making the resources suited to diverse users. Basic outreach activities (such as opening social media accounts or creating online content with no focus on dissemination) are insufficient and fail to reach a wide population. Therefore, the pilot utilizes a wide range of collaborations, together with the informed feedback from a Delphi study, to create, test, and improve a network of dissemination for quantum education-related materials, which will be beneficial to the entire community. Overall, the pilot represents a backbone on which the diverse resources created by the partners can be synergistically made available to boost outreach and education.

In summary, the planned actions include the following. First, we will produce the production of an essential syllabus of quantum physics concepts and their main applications to quantum technologies, identifying for each the type of beneficiary, already-existing educational resources and a list of the missing ones, the learning outcomes, the best-suited type of symbolic/language system, relevant assessment tools, and, coherently with the RRI dimensions, potential applications that the pilot can focus on including public health, the environment, and communication. Second, we will conduct a Delphi study with QTEdu participants and associated parties aimed at identifying stakeholders, opportunities, and problems in QT outreach and engagement activities, as well as practical solutions. The study outcomes are expected to represent a guide for future design of outreach and educational resources that can be disseminated to diverse and extended audiences. Third, we will organize joint outreach virtual activities, including live panels for the European Researchers' Night, hackathons, quantum game jams, showcases for games and virtual experimental, and simulation platforms and a joint program of events for the World Quantum Day. Finally, we will focus on the assessment of the coherence of the pilot deliverables with RRI dimensions, which is achieved by defining a checklist for each individual dimension and specific type of resources and activities that define the six-by-six matrix described above, and finally applying the checklist to the pilot deliverables. This checklist will be produced via a planned RRI training activity for PhD students from different disciplinary areas. Via this synergetic action, QUTE4E aims to both assess its internal RRI coherence and, at the same time, provide an RRI measurement tool for education and outreach in quantum physics and technologies.

6 Conclusion

In this article, we introduced a wide range of quantum games and interactive tools that have been used across the community for several years for QT outreach and education. Subsections on these tools were written by their developers for them to describe their work in their own words, to share their experiences from the field of games/tools development for outreach and education purposes. In addition, we covered examples of two different types of activities, quantum game hackathons/jams, and semester projects for quantum game development. Finally, we described the QUTE4E pilot project under the QTEdu Coordination and Support Action within the European Quantum Flagship Program as an example of how utilization and development activities of such tools can be integrated with quantum outreach and education efforts. These examples were provided to give readers guidance in formulating creative projects and to enhance institutions' capacity to launch pioneering initiatives.

The wide range of games and tools provided here cannot be evaluated from a comparative point of view due to the lack of comprehensive assessment tools in the literature. It is important to develop approaches to evaluate the performance efficiency and effectiveness of the games and tools presented here. The challenge lies in identifying the purpose and scope of their use as they address diverse needs in education, outreach, and research.

The quote "Quantum computing is a marathon not a sprint"[202] is widely used within the community. It is important to add here that this marathon is one that has significant implications for the future of technology and its impact on society.[13,15] Hence, the widest possible participation and engagement by the stakeholders within society should be targeted. We hope that the illustrative examples provided in this article, including games, tools, events, and models, can serve as a solid departure point for current and future practitioners of quantum outreach and education.

Acknowledgments

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