

Exploring quantum physics through play: integrating games, experiments, mathematics, and art in STEM education: Using game-based, inquiry-based, and creative approaches to teach quantum concepts

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Abstract: Quantum technology is one of the most challenging areas of science to introduce into school education because of the abstract nature of its fundamental concepts, their distance from everyday experience, and the need to connect conceptual, physical, mathematical, and experimental approaches. This paper presents “Quantum World Through Play,” an innovative educational project designed to introduce upper-primary and secondary school students to fundamental concepts of quantum physics and quantum computing through games, experiments, simulations, and creative activities. The project was developed within the international Quantum Computing in STEM Education initiative organised by Science on Stage, which brought together STEM teachers from different European countries to develop and exchange educational materials and teaching approaches. The educational model consists of four interconnected workshops: the historical development of quantum physics, learning quantum concepts through board games, exploring mathematical and experimental aspects of quantum phenomena, and connecting quantum physics with art. The project combines physics, mathematics, and creativity and provides an adaptable model for different age groups and levels of prior knowledge. The paper describes the pedagogical design, interdisciplinary structure, and potential educational benefits of the project and proposes a framework for future empirical evaluation.

Keywords: quantum physics, STEM education, game-based learning

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1 Introduction

Quantum science and technology are becoming increasingly important in contemporary science, engineering, and technological development. Quantum principles underpin technologies including lasers, magnetic resonance imaging, quantum sensors, communication technologies, and emerging quantum computers.

The growing importance of quantum technologies creates a need to introduce basic quantum concepts to students at an earlier stage of education. This need was further



highlighted by the designation of 2025 as the International Year of Quantum Science and Technology, coordinated by UNESCO and the United Nations, which aimed to increase public understanding of quantum science and promote educational opportunities in this field (United Nations General Assembly, 2024).

However, introducing quantum physics into school education presents significant pedagogical challenges. Concepts such as superposition, quantum entanglement, measurement, and probabilistic outcomes are difficult to connect with students' everyday experiences. Traditional approaches based primarily on mathematical formalism may also make quantum physics inaccessible to younger learners. Research suggests that interactive and game-based approaches can provide alternative ways of introducing difficult quantum concepts. For example, Chiofalo et al. (2022) investigated the use of games for teaching quantum mechanics to high-school students and reported positive effects on students' engagement and conceptual understanding.

In response to these challenges, the project “Quantum World Through Play” was developed as an interdisciplinary educational model combining games, experiments, mathematics, and art.

1.1 Quantum World Trough Play

The Quantum World Through Play project was developed in response to the growing importance of quantum science and quantum technologies and the challenges associated with introducing these complex and often counterintuitive concepts at school level. Its overarching aim is to develop and implement an interdisciplinary, accessible, and pedagogically grounded approach through which upper-primary and secondary school students can encounter the fundamental ideas underlying quantum physics and quantum computing. Rather than presenting quantum science exclusively through formal mathematical explanations, the project seeks to connect abstract concepts with students' existing knowledge and experiences through active, experiential, game-based, experimental, and creative learning.

The project introduces students to fundamental concepts of quantum physics and quantum information science, including probability, quantum states, superposition, measurement, and entanglement. Particular attention is given to supporting conceptual understanding of phenomena that are difficult to interpret using classical teaching models. Through games, experiments, simulations, visual representations, and guided inquiry, students are encouraged to explore these phenomena, formulate questions, make predictions, analyse observations, and develop their own explanations before being introduced to more formal

scientific descriptions.

An important dimension of the project is its interdisciplinary character. Quantum science provides a natural context for connecting physics with mathematics, games, and art. Mathematics provides tools for describing probability, vectors, matrices, and quantum states, while artistic activities provide alternative ways of representing and communicating abstract scientific ideas. In this way, students are encouraged to perceive STEM disciplines not as isolated areas of knowledge but as interconnected approaches to understanding complex phenomena.

The project also aims to strengthen students' engagement with STEM subjects by presenting quantum science as a contemporary and rapidly developing field with relevance to emerging technologies and future scientific and professional opportunities. This dimension is particularly important in the context of current international initiatives in quantum education, which seek to increase young people's awareness of quantum technologies and develop the knowledge and skills needed for an increasingly quantum-enabled society.

A further objective is to develop transferable competencies, including critical thinking, problem-solving, scientific reasoning, creativity, collaboration, and scientific communication. The learning activities are therefore designed not simply to transmit scientific information but to provide opportunities for students to work collaboratively, investigate problems, evaluate evidence, communicate their ideas, and approach unfamiliar situations systematically.

Game-based learning represents a central methodological component of the project. Games provide students with opportunities to interact with simplified models of quantum systems, make decisions, observe probabilistic outcomes, and reflect on the consequences of different actions. In this context, games are not regarded merely as motivational activities but as pedagogical representations that can support students in developing conceptual models of phenomena that are otherwise difficult to visualise.

The project is also designed to accommodate differences in students' prior knowledge and abilities. Activities can be implemented at different levels of complexity, allowing students with limited mathematical or scientific backgrounds to participate in conceptual and experimental activities while providing more advanced learners with opportunities to engage with mathematical representations, quantum circuits, simulations, and computational tasks. This approach supports differentiated and inclusive learning and makes quantum education more accessible across different educational contexts.

An additional objective is to support teachers as facilitators of quantum education. The project therefore includes adaptable teaching materials and methodological guidance that can be used by teachers from different disciplinary backgrounds. The resources are intended to facilitate the integration of quantum concepts and interdisciplinary STEM lessons without requiring teachers to have advanced prior expertise in quantum computing. The project was developed within the international Quantum Computing in STEM Education initiative organised by Science on Stage, which brought together STEM teachers from different European countries to develop and exchange educational materials and teaching approaches (Science on Stage, 2026). The project was implemented at Petro Kuzmjak School in Serbia between 2024 and 2026, providing 63 students of high school age (16-18) with opportunities to explore fundamental concepts of quantum computing through a variety of interactive, interdisciplinary, and experiential learning activities.

1.2 Challenges in teaching quantum physics at school level

Teaching quantum physics at school level presents particular pedagogical challenges because quantum theory differs from classical physics not only in the mathematical formalism used to describe physical systems, but also in the conceptual framework required to interpret physical phenomena. Many of the concepts introduced by quantum mechanics are counterintuitive when viewed from the perspective of students' everyday experiences and their prior knowledge of classical physics.

Students often attempt to interpret quantum phenomena using familiar classical models, which can lead to persistent misconceptions about the nature of quantum states, the role of measurement, the meaning of probability, wave-particle duality, superposition, and entanglement. For example, concepts such as superposition and entanglement cannot be understood adequately by simply applying classical ideas about objects, states, and physical interactions. Consequently, students may develop simplified interpretations that provide an intuitive explanation but do not accurately reflect the underlying scientific concepts.

These challenges are well documented in the research literature. In their systematic review of research on teaching quantum mechanics at secondary and lower-undergraduate levels, Krijtenburg-Lewerissa et al. (2017) identified substantial difficulties in students' understanding of several fundamental concepts, including superposition, wave functions, time dependence, potential wells, and the measurement problem. Their review also highlighted a lack of sufficient empirical evidence concerning which instructional approaches are most effective in supporting students' conceptual understanding of quantum mechanics. These findings are particularly relevant to secondary education, where students

are often introduced to quantum physics with limited mathematical preparation and relatively little opportunity to engage with quantum phenomena experimentally. Simply transferring approaches developed for university-level quantum mechanics to the school context may therefore be insufficient. Effective school-level instruction needs to take into account students' existing conceptions and provide an appropriate progression from intuitive experiences toward increasingly formal scientific models. For this reason, quantum education should incorporate a variety of representations and learning experiences. Students need opportunities to encounter abstract concepts through visual models, physical and digital simulations, experiments, mathematical representations, discussion, collaborative activities, and carefully designed analogies. At the same time, these representations need to be accompanied by explicit discussion of their limitations in order to prevent new misconceptions from emerging. Providing opportunities for students to make predictions, test their ideas, analyse evidence, and discuss alternative explanations can further support the development of conceptual understanding.

Another important consideration is mathematical readiness. Although an introductory understanding of quantum phenomena does not necessarily require advanced mathematics, mathematics provides an increasingly important language for expressing quantum states and probabilities as students' progress. Effective instruction should therefore establish connections between conceptual exploration and appropriate mathematical representations rather than treating these as completely separate forms of knowledge. The Quantum World Through Play project responds to these pedagogical challenges by combining several complementary modes of learning. Through games, simulations, mathematical activities, historical inquiry, discussion, and artistic expression, the project provides students with multiple opportunities to approach the same quantum concepts from different perspectives. This multimodal approach is intended to create a gradual transition from intuitive and experiential learning toward more formal scientific understanding, while also allowing students with different levels of prior knowledge to engage meaningfully with quantum science.

2 Pedagogical model

The Quantum World Through Play project was designed as a four-workshop pedagogical model that progressively introduces students to fundamental concepts of quantum physics and quantum computing through historical inquiry, game-based learning, mathematical modelling, experimentation, and artistic expression. The workshops are interconnected and follow a progression from contextual and experiential learning toward conceptual and

mathematical formalisation, while maintaining opportunities for reflection and creative communication.

The model is based on the assumption that quantum concepts are particularly challenging for school students because they are often inconsistent with classical intuitions. Consequently, the project does not introduce quantum physics exclusively through formal mathematical descriptions. Instead, different representational and experiential approaches are combined to provide students with multiple entry points into the subject.

2.1 A journey through the history and experiments

The first workshop introduces quantum physics through the historical development of scientific ideas. Rather than presenting quantum theory as a completed body of knowledge, the activity places its development within the broader context of scientific discovery, questioning, experimentation, and theoretical debate.

Students collaboratively construct a chronological timeline beginning with Max Planck's introduction of the quantum hypothesis and continuing through major developments associated with Albert Einstein, Niels Bohr, Erwin Schrödinger, and other scientists who contributed to the emergence of quantum theory. The timeline subsequently extends toward contemporary developments in quantum information science and quantum computing.

Role-playing activities are incorporated to allow students to investigate the contributions and perspectives of individual scientists. By assuming the roles of historical figures, students are encouraged to consider not only scientific discoveries but also the questions, problems, and competing interpretations that shaped the development of quantum physics.

From a pedagogical perspective, this approach serves two complementary purposes. First, historical contextualisation provides students with a meaningful framework for understanding otherwise abstract concepts. Second, it presents scientific knowledge as the result of an iterative process involving observation, hypothesis formation, theoretical development, experimentation, discussion, and revision, rather than as a static collection of established facts.

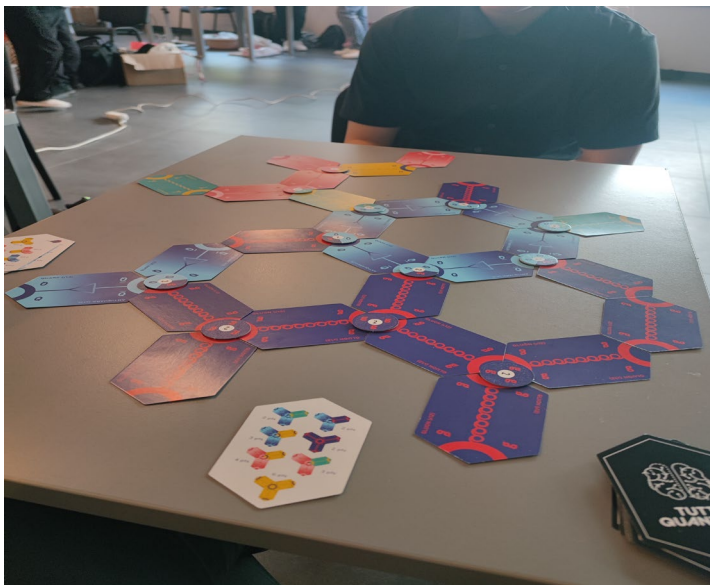
Following the historical component, students are introduced to fundamental concepts including quantisation, probability, quantum states, superposition, measurement, and entanglement. These concepts are presented initially at a conceptual level and subsequently connected to contemporary applications of quantum physics, including quantum computing and other quantum technologies.

The workshop therefore establishes the conceptual and historical foundation for the subsequent activities, while also helping students recognise the continuity between the historical development of quantum theory and current technological advances.

2.2 Quantum physics through game

The second workshop applies game-based learning as the primary pedagogical approach. Students work collaboratively with educational games and structured activities designed to provide simplified representations of selected concepts from quantum physics and particle physics. The second workshop employs game-based learning as an introductory approach to particle and quantum physics. Existing educational games, including Elementary – A Physics Game and Tutti Quantum – The Game of Elementary Particles, are used to familiarise students with elementary particles, their properties, interactions, and graphical representations. These activities provide a conceptual foundation for subsequently introducing quantum phenomena and quantum information concepts. The workshop is complemented by teacher-developed games specifically designed to address concepts such as probability, measurement, quantum states, superposition, and quantum operations. Game-based learning activities can provide an accessible introduction to particle and quantum physics by allowing students to explore scientific concepts through interaction, classification, and problem-solving rather than memorisation. Elementary – A Physics Game, developed by Serafine Beugelink, introduces students to elementary particles such as quarks, leptons, bosons, and antiparticles through card-based gameplay in which players collect and combine particles according to their properties. Similarly, Tutti Quantum – The Game of Elementary Particles, designed by Francesco Riva and Ajša Zdravković as part of the UNSOLVeD project, enables students to explore particle interactions by constructing simplified Feynman diagrams according to established physical rules. Together, these games provide an accessible conceptual pathway from elementary particles and their properties to particle interactions, graphical representations, and the foundations of modern quantum science. In the Quantum World Through Play project, they can therefore serve as introductory activities that prepare students for more advanced exploration of quantum phenomena and quantum computing. During the experience stage, students interact with the game environment and follow its rules without necessarily receiving a complete theoretical explanation beforehand. This allows them to encounter patterns, probabilistic outcomes, constraints, and unexpected results directly through interaction. In the figure we can see a student playing game.

Figure 1. Student plays game related to quantum concepts



This sequence is intended to ensure that gameplay functions as a pedagogical mechanism rather than merely as an entertaining addition to conventional instruction. The game serves as a mediating representation through which students can encounter, manipulate, and discuss simplified models of otherwise abstract phenomena. Such an approach is consistent with research suggesting that games can provide meaningful contexts for engagement with non-intuitive quantum concepts.

An important methodological consideration is that the limitations of each game or analogy should subsequently be discussed explicitly. A simplified game cannot reproduce the full mathematical or physical structure of a quantum system; therefore, teacher-guided reflection is necessary to distinguish the educational model from the underlying physical phenomenon.

2.3 Mathematics and experimental learning

The third workshop establishes a connection between students' conceptual experiences and the mathematical formalism used to describe quantum systems. The workshop is structured progressively so that mathematical representations are introduced as tools for explaining phenomena that students have previously encountered through experiments and games.

The initial activities focus on probability and randomness. Students conduct simple experiments using dice, coins, or other random processes and analyse the resulting distributions. These activities provide a familiar context for discussing probability before introducing the ways in which probability is represented in quantum measurement.

For students with more advanced mathematical preparation, the workshop can be extended to include vectors, matrices, complex numbers, probability amplitudes, quantum states, qubits, and quantum gates.

At an introductory level, a qubit can be represented as a quantum system described using two computational basis states, $|0\rangle$ and $|1\rangle$. A general pure qubit state can then be expressed as

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle,$$

where α and β are complex probability amplitudes satisfying the normalisation condition

$$|\alpha|^2 + |\beta|^2 = 1.$$

The purpose of introducing this representation at school level is not necessarily to require students to perform advanced quantum-mechanical calculations. Rather, the mathematical expression demonstrates how mathematical formalism can provide a precise language for describing quantum states and the probabilities associated with their measurement outcomes.

The level of mathematical formalisation can subsequently be differentiated according to students' prior knowledge. Younger or less mathematically prepared students may work primarily with visual representations and probability experiments, while more advanced students can explore vector representations, matrix operations, quantum gates, and simple quantum circuits. In the figure we can see the part of lesson plan (Science on Stage, 2026).

Figure 2. Part of lesson plan

The screenshot shows the 'SCIENCE ON STAGE EUROPE' website. At the top, there are navigation links: 'Teaching Materials', 'For teachers', 'Partners & Supporters', and 'Latest'. Below this is a yellow banner with the text '3.1 Probability' and a right-pointing arrow. Under the banner, the section 'Basic definitions of probability theory' is highlighted. The text in this section defines a sample space (Q) as the set of all possible outcomes of a random experiment, gives examples for a coin flip and a six-sided die, defines events (E) as collections of outcomes, and defines the probability p(E) of an event E as a number between 0 and 1.

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3.1 Probability

Basic definitions of probability theory

A sample space (usually denoted as Q) is the set of all possible outcomes of a random experiment.
For example, when flipping a coin, the sample space is {Head, Tail}. When rolling a six-sided dice, the sample space is {1, 2, 3, 4, 5, 6}.

Events (E) are certain collections (subsets) of outcomes from the sample space.
An event E is a set of outcomes of a random experiment. For a coin flip, one event could be "getting Head" and another event could be "getting Tail". There is even an event that includes all possible outcomes: "getting Head or Tail".

Probability of an event

The probability $p(E)$ of an event E is a number between 0 and 1 such that:

This progression from concrete experience to conceptual representation and, where appropriate, mathematical formalisation is an important principle of the proposed pedagogical model. It allows mathematical concepts to emerge from previously established physical and experiential contexts rather than being introduced as isolated symbolic procedures.

Experimental activities constitute an additional component of the pedagogical model and provide opportunities for students to connect theoretical concepts with observable phenomena. The purpose of these activities is not simply to demonstrate established scientific principles, but to encourage students to formulate predictions, make observations, compare results with expectations, and reconsider their initial explanations.

One of the proposed activities involves the double-slit experiment, using a laser to demonstrate the phenomenon of optical interference. The resulting interference pattern provides a starting point for discussing wave behaviour, interference, probability, measurement, and the limitations of classical interpretations.

This approach is particularly relevant to quantum education because students frequently enter the classroom with well-established classical conceptions. Creating opportunities for them to confront their predictions with experimental evidence can provide a basis for conceptual development.

2.4 Quantum physics and art

The fourth workshop extends the STEM framework into STEAM (Science, Technology, Engineering, Arts, and Mathematics) by introducing artistic and creative representation as an additional means of communicating and reflecting on quantum concepts.

Students were invited to represent concepts such as superposition, entanglement, probability, and uncertainty through a variety of media, including drawings, digital artwork, posters, visual metaphors, conceptual maps, creative writing, and three-dimensional models.

For example, students created visual representations inspired by the concept of superposition, use interconnected structures to represent aspects of entanglement, or generate patterns based on probability distributions to communicate ideas related to quantum uncertainty.

The purpose of these activities is not to suggest that an artistic representation constitutes a scientifically complete model of a quantum system. Rather, artistic production is used as a representational and communicative tool that allows students to externalise their interpretations, communicate abstract ideas, and reflect on their developing understanding.

This distinction is particularly important in science education because metaphors and visual representations can facilitate initial understanding while simultaneously introducing potential misconceptions if their limitations are not made explicit. Consequently, artistic activities are followed by discussion in which students explain the scientific meaning they intended to communicate and identify aspects of their representation that do not correspond directly to the underlying physical model.

The integration of art is also consistent with the broader interdisciplinary philosophy of the project. Mathematics and science are often perceived by students as highly formal disciplines, while artistic activities provide opportunities for creativity, visual thinking, personal expression, and communication. Bringing these approaches together can demonstrate that scientific concepts can be explored and communicated through multiple forms of representation.

In this respect, the Quantum World Through Play project treats art not simply as an additional creative activity but as a complementary mode of scientific communication and reflection. The approach is particularly aligned with the project's broader objective of connecting mathematics, science, technology, and creativity and demonstrating that abstract mathematical and scientific ideas can be explored through both analytical and artistic perspectives. In the figure we can see students' artwork.

Figure 3 Students artwork inspired by quantum physics



3 Conclusion

“Quantum World Through Play” presents a pedagogical model for introducing quantum physics and quantum computing through an interdisciplinary combination of games, experiments, mathematics, computer science, history, and art.

The model builds on the international Science on Stage Quantum Computing in STEM Education initiative, which demonstrates the value of teacher-driven international collaboration in developing practical resources for quantum education. Twenty teachers from fifteen European countries collaborated to develop, test, and refine materials for classroom use. It was applied in Petro Kuzmjak school with highschool students.

The proposed project extends this approach by placing particular emphasis on game-based learning and creative representation. Its four workshops provide students with multiple opportunities to encounter quantum concepts through experience, discussion, experimentation, mathematical representation, and artistic expression.

Existing research provides promising evidence for the use of games and experiential approaches in quantum education but also demonstrates the need for further empirical research. The project should therefore be understood not simply as a collection of engaging classroom activities but as a structured interdisciplinary learning model that can be empirically evaluated and further refined. Its long-term value lies in creating a pathway through which students can move from curiosity to conceptual understanding and, ultimately, to meaningful engagement with one of the most important scientific and technological fields of the twenty-first century.

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