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A Survey on Quantum Literacy within Gamification in Science Education

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Abstract

During quantum era, new rules governing physical phenomena and reality contribute to the development of quantum technology, which will change people's lives, in the near future. A great range of quantum technologies, based on quantum information theory and quantum computing, lead to new applications. Revolutionary quantum computing algorithms benefit from basic quantum mechanics properties, such as entanglement and superposition effects, to advance calculations in polynomial time. In essence, Quantum Mechanics (QM) is considered a cross – disciplinary STEM Physics field, aiming to advance the philosophy of Quantum Literacy (QL), which addresses the transdisciplinary nature of real world complex problems. QL addresses the challenges of quantum technologies learning and skills acquisition, through gamification and computing problem – solving environments. Simulations, virtual labs and interactive tools through serious games, create an attractive learning environment and promote at the same time an interdisciplinary field of physics, technology and information sciences. Technological interventions, often combined with contemporary teaching methods, provide guidelines for better and long-lasting learning outcomes. To this end, literature often emphasizes students' engagement with serious games, especially if the content is interdisciplinary and lies in the crossroad section of Physics, Mathematics, Computer and Computational Sciences.

Our work focuses on mapping the State of the Art among contemporary teaching methods and gamification techniques and tools, as applied for quantum mechanics concepts and quantum computing problems, to best advance QL. We also discuss the trends among contemporary teaching methods, effective gamification tools and quantum learning topics, fostering quantum physics knowledge from K-12 educational level.

Keywords: Quantum Literacy, Quantum Serious Games, Contemporary Teaching Methods, Basic Quantum Concepts, k-12 Education

1. Introduction

The rapid development of new Quantum Technology and its applications, contributes to a QL worldview (Chiofalo *et al*., 2021) [12]. QL *is about "learning of the minimal body of fundamental knowledge of quantum mechanics that allows understanding of how quantum computation could be used in diverse application domains and the capability to assess claims related to quantum technology"* (Nita *et al*., 2020) [57]. For an efficient quantum leap we should focus on quantum education by building scientific thinking and powerful knowledge accessible to a wide group of learners and stakeholders, starting from K-12 education level (Curioni, 2022) [14]. Quantum education addresses the challenge on how students understand basic quantum ideas and apply quantum principles to solve complex interdisciplinary problems. This task is more feasible through gamification and computing problem – solving environments (Xenakis *et al*., 2023; Chiofalo *et al*., 2021) [88, 12].

QL, with its foundations to quantum information theory, computing frameworks and quantum communications, offers a more thorough way of conceiving problems in a range of diverse fields (Matsler, *et al*., 2020) [53]. Quantum information is based on *qubit,* which is the smallest information unit, to replace the binary bit of classical computer systems. This quantum mechanical system is based on spin position to calculate a problem's solution in polynomial time, no matter its complexity (Kory, 2019) [43]. Quantum information, exploits quantum principles for the storage, transmission, manipulation, processing, or measurement of information. Multinational technology companies such as IBM and Google, benefit quantum principles in order to build more powerful computers which beat the today's world best conventional supercomputers. Their computing power is based to quantum supremacy (Cho, 2019) [15]. Quantum technology is expected to provide new products and services for various market domains, such as pharmaceutical industry, health care, chemistry, finance, logistics, etc. (Claridge, n.d.) [16].

Principles of Quantum theory constitute the basis for a constructive quantum education, according to which, students may experience and explore quantum principles and their applications. Nowadays, school curricula focuses on highlighting the profound differences between classical and quantum physics, through abstract mathematical formalism, which is hard for students to comprehend (Pospiech 2021; Palmgren *et al*., 2022) [70, 63]. In Quantum mechanics education there are several concepts (e.g. probability, quantum superposition) which are counterintuitive and conflict with the classical worldview, which is more familiar to students. Thus, the teaching methods to address core quantum mechanics concepts need to change and support gamification and experimentation. Professor Emeritus Anthony James Leggett said: "*Quantum mechanics is more than just a theory, it is a new way of seeing the world, it pushes us to go beyond the comfort zone and conventional frameworks of our minds and move on to new and innovative situations"* (Xenakis *et al*., 2023) [88].

To this end, students' education is carried out through crossdisciplinary activities enhancing the active-learning and problem-solving skills. This style of teaching in terms of STEM, prepares students to solve real-world complex problems through innovation, critical thinking, creativity, collaboration and ultimately new knowledge (Quigley & Herro, 2016) [71]. Recently, traditional teaching is increasingly supported by digital technology (Freericks, 2019; Rodrigues, 2020; Bitzenbauer, 2022) [30, 72, 8] such as simulations and interactive tools, enhancing visualization and experiential learning across an attractive learning environment. Therefore, teaching process requires careful alignment of theoretical aspects and visualization by various representations, by suitable well-chosen metaphors and model experiments. Especially in Science education, the way the instructional content is presented is just as important as visualizations and interactive tools.

Student-centered teaching methods such as: Inquiry-based, problem- based, project- based or gamification techniques provide student's conceptual awareness of scientific concepts (Toriz, 2019; Nyirahabimana *et al*., 2023) [79, 60]. Also, interactive environments help students to construct their own knowledge fostering problem-solving and self-directed learning skills (Walsh *et al*. 2022; Xenakis *et al*., 2023) [84, 88]. In addition to this, contemporary teaching methods combined with technological interventions, provide guidelines for better and long-lasting learning outcomes. To this end, the contribution of this paper is twofold:

- To map the state-of-the-art among contemporary teaching methods, gamification techniques and tools, as applied for quantum mechanics concepts and quantum computing problems, to best advance QL.
- To discuss the trends among gamification tools, quantum learning topics and contemporary didactic approaches fostering quantum physics knowledge in K-12 education.

Our work is organized as follows: In **section 2** we give a brief background in terms of key quantum concepts, along with the contemporary didactic approaches to support quantum knowledge. In **section 3** we present related works on how basic quantum concepts are approached among contemporary teaching methods, active learning techniques and interactive gamified simulations. Also, we point out the evaluation of quantum games and basic quantum topics in a learning process. In **section 4** we discuss the trends among contemporary didactic methods, effective gamification tools, and learning quantum topics fostering quantum physics knowledge in K-12 educational level. Finally, **section 5** concludes the paper.

2. Preliminaries – Background

2.1 Basic Key Concepts for Quantum Knowledge

Developing the philosophy of QL, student's education in Quantum Theory addresses the challenge on how students acquire core quantum principles and apply them in quantum computing environments to solve complex interdisciplinary problems. To best advance this task, it is essential to briefly state the meaning of core quantum mechanics and quantum computing concepts as defined in the cross-disciplinary fields of physics, technology and informatics sciences. In particular:

1. Qubit: Is the smallest unit of Quantum computer's information which replaces the binary bit of classical computer's. Classical bits can be found in two logical states: 0 or 1, qubit instead could be found in states 0, 1 or in *superposition* of both. Qubit's states can be physically represented as a two-state system e.g. the spin direction of the electron (spin up, spin down) or the polarization of a single photon (vertical polarization, horizontal polarization), as illustrated in Fig 1 (Chen *et al*., 2009) [19]. Geometrically, qubit can be visualized as a 2-D vector in a sphere known as Bloch sphere as presented in Fig 2. Bloch sphere is a 3-D Hilbert space of a quantum system state in which the projection of the vector is measured along a specified axes e.g. x, z in order to determine the *state* of a qubit (Avramouli *et al*., 2023) [1]. In other words, if a qubit represents a physical system as for example the spin of a particle, with the feature of receiving only two possible values (i.e. up and down), the Bloch sphere is the space where almost all the features of a qubit are depicted (Chen *et al*., 2009) [19].

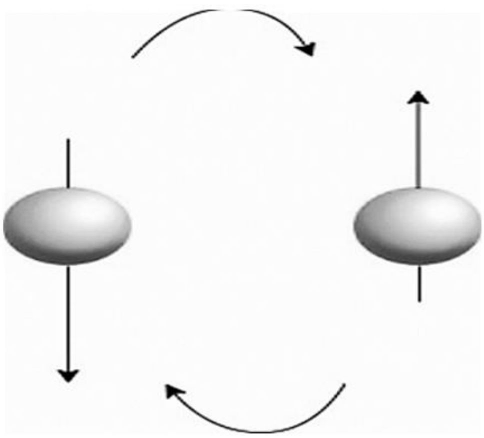

Fig 1: Representation of qubits spin-state

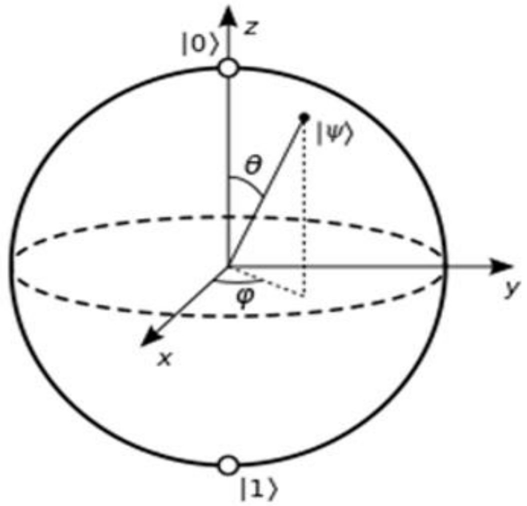

Fig 2: Representation of Bloch sphere

2. Quantum Superposition: Is the ability of a quantum system to be in multiple states simultaneously (Xenakis *et al*., 2023) [88]. For example, if we had a *particle* (e.g. an electron) in superposition that means it could move fast and slow at the same time, in other words at the same time it could have two different states of motion or energy. Qubit is based on this fundamental quantum concept, in which qubit's state could be *observed* in |0>, |1> or in a linear combination (i.e. superposition) of these two states when it is *measured*. Through Quantum superposition, a solution of a problem is calculated in polynomial time, no matter its complexity.

3. Quantum Entanglement: Is the phenomenon that two quantum particles remain in contact and interact with each other (i.e. linked) no matter how far apart they are. Particles are described by a *wave function* which contains the combined and common information about the quantum states of both particles (Xenakis *et al*., 2023) [88]. For example, if we have two entangled qubits and one of them is led to superposition, then the other will also be led to superposition instantaneously. Entanglement is part of what gives quantum computers greater power than classical ones.

4. *Quantum Measurement:* Is the procedure in which we *observe* a quantum particle in order to measure its properties (e.g. position or spin). For example, in computational problems, we observe the state of a qubit through measurement (Weisz *et al*., 2018) [85]. Quantum measurement also, is closely related to the term *collapse of the wave function*. For example, if we measure a qubit's state in a quantum superposition, the qubit's state is instantly transformed from a superposition of states into a definite (i.e. classical) state with a well-defined value as depicted in Fig 3. So, this transformation corresponds to a *collapse* of the information (i.e. wave function).

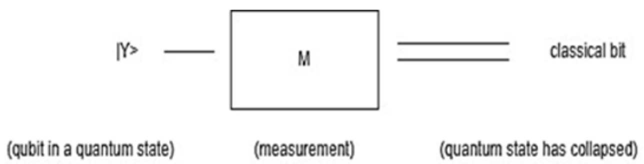

Fig 3: Representation of quantum measurement on a qubit

5. Quantum state: In Physics, state is a term which is often used to describe a system within a set of variables. Classical state of a physical system as for example a state of motion of a ball could be described by distinct variables i.e. the velocity and the direction. Quantum state of a quantum system is a mathematical description with a set of quantized variables (Chandralekha *et al*., 2022) [17]. The mathematical description (also called *Dirac notations*) of a quantum state can be represented as a 2-d vectors:

$$|0\rangle = \begin{bmatrix} 1 \\ 0 \end{bmatrix} \qquad |1\rangle = \begin{bmatrix} 0 \\ 1 \end{bmatrix}$$

The state vector can be physically represented in the Bloch sphere, as shown in Fig 2. For example if we had to describe a state of a quantum coin, the possible solutions could be the heads (i.e. |0>), tails (i.e. |1>) or the superposition of both (i.e. a|0> +b|1>, where a and b are probability amplitudes (complex numbers) satisfying the normalization criteria: $|a|^2 + |b|^2 = 1$) (Xenakis *et al*., 2023) [88].

***6. Quantum logic circuit*:** In Quantum computation, quantum logic circuit is a model in which a computation is a sequence of quantum logic gates, measurements, initializations of qubits to known values etc. In other words, a circuit describes how a qubit's state changes through a computation depending on which gates act on it (Hughes *et al*., 2021) [38]. Quantum gates, unlike classical logic gates, operate on a small number of qubits simultaneously (i.e. in all possible states of qubits) and they are reversible (Avramouli *et al*., 2023) [1]. Also, a program or algorithm consists of many quantum logic gates. There are quantum gates which manipulate a state of a single qubit (e.g. Hadamard, Pauli gates) or more qubits (e.g. controlled gates). Following, we mention some of the most significant quantum gates and their operations:

i) ***Hadamard gate (H gate)*:** Hadamard gate facilitates the transformation of a qubit from a single computational basis state to a superposition state and vice versa. For example, if we have a qubit in a computational state |0> by applying a Hadamard gate we have the following output:

$$H|0\rangle = \frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle$$

In other words, a Hadamard gate forces a qubit to have a 50% probability of collapsing to |0> computational state and a 50% probability of collapsing to |1> state (Marckwordt *et al*., 2021) [54] as depicted in Fig 4.

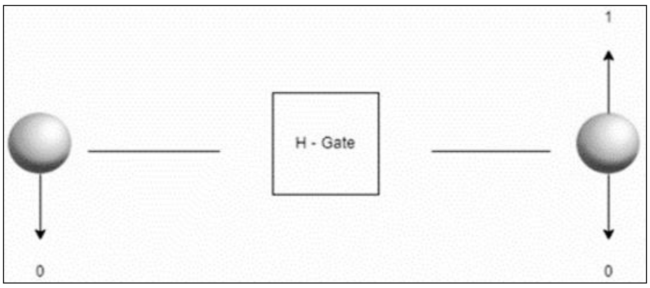

Fig 4: Optical representation of the Hadamard gate operating in a state of a single qubit

ii) ***Pauli X-gate (X gate):*** The Pauli-X gate represents a single-qubit rotation by π radians around the x-axis of the Bloch sphere. Generally, there are three Pauli gates (x, y, z) which equate respectively, to a qubit rotation around the x, y, z-axis respectively of the Bloch sphere by π radians.

Mathematically, if a computational state of a qubit is |0>, through X- gate flips to |1> and vice versa (Hughes *et al.*, 2021) [38] as illustrated in Fig 5.

Fig 5: Optical representation of the Pauli-X gate operating in a state of a single qubit

iii) ***C-Not gate (CNOT or CX):*** The CNOT gate is a two-qubit operation, where one qubit is usually referred as the *control* qubit and the other as the *target* qubit, as depicted in Fig 6. In more details, if we have two qubits the CNOT gate applies an X-gate to the target qubit' state only if the control qubit is in computational state |1>. In case of the control qubit's state is |0>, the target qubit's state remains unchanged. In both cases, the control qubit's state remains unchanged during this process (Just, 2023; Wonk, 2022) [31, 86].

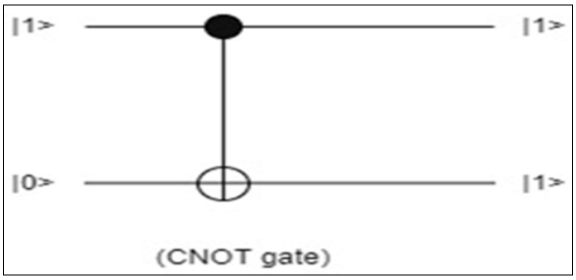

Fig 6: Optical representation of the CNOT gate operating in two qubits states

iv) ***Swap gate (SWAP):*** A SWAP gate, is a two-qubit operation which swaps the numbers in the basis computational states (Wonk, 2022) [86]. For example, if we have two qubits in computational state |01>, by applying a SWAP gate we get |10>. Also, a SWAP gate can be implemented in a quantum circuit by using three CNOT gates in sequence as depicted in Fig 7.

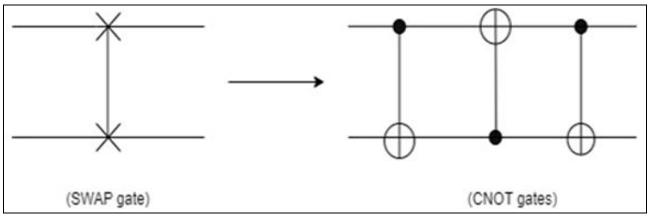

Fig 7: Optical representation of the SWAP gate (left graph) and three CNOT gates in sequence (right graph) in two qubits states

2.2 Contemporary Didactic Approaches for Quantum Knowledge

The transformation of education, according to the Education 4.0 framework utilizes advanced technological developments as well as new emerging needs, redefining learning and teaching process as a completely new experience (Patiño *et al.*, 2023) [64]. Contemporary teaching and learning methods, as applied through gamified or interactive simulations for science education, it is an essential need for students to have an active role in the learning process and influence their attitudes and achievements. Students' difficulties with learning quantum mechanics (e.g. abstract concepts, complex mathematics and visual representations) has been growing steadily over the past two decades. As a consequence, a pedagogical method, called ***Spin First*** approach, which began to emerge in teaching quantum mechanics, was crucial (Sadaghiani, 2015; Palmgren, 2022; Corcovilos, 2018) [78, 63, 23]. The Spin First (SF) approach introduces the fundamental concepts of QM through the analysis of sequential *Stern-Gerlach* spin experiments with discrete two state spin-half bases.

This approach allows students to first focus on abstract concepts while the mathematics are simple and limited to two discrete states of spin-half. In addition, students may find it more accessible and relatable, especially since spin is analogous to the familiar concept of angular momentum in classical mechanics. Mathematically, two state spin-half is one of the simplest, yet most instructive examples with concrete experimental basis (Sadaghiani, 2015) [78]. The Spin first approach requires much simpler processes and calculations, and is limited to two-by-two matrices. Commencing with concepts based on experimental results allows students to focus on understanding rather than problem-solving performance. In this approach, Dirac and bra-ket notation for states, observables, and projection operators is used from the very beginning (Sadaghiani, 2015; Palmgren, 2022) [78, 63].

Inquiry is a method which involves engaging students in using critical thinking skills, for example making questions, designing and carrying out investigations, interpreting data as evidence, creating arguments, building models and solving real complex problems, as depicted in Fig 8 (Strat & Jegstad, 2023; Karamustafaoğlu *et al.*, 2023 [45]). In Science education inquiry, is associated with the processes and method used by scientists in essence how science proceeds and how new information and understanding is developed using scientific processes (Cairns *et al.*, 2019) [18]. ***Inquiry-based learning*** (IBL) is a student learning process based on inquiry methods, providing students of how scientists proceed in the real world enhancing scientific learning. IBL, is defined as a student-centered methodology which improves students' attitude while acquiring of science concepts.

In the same context, ***Problem-based learning*** (PBL) is a student learning methodology which is well combined with problem- solving scenarios (Xenakis *et al.*, 2023; Hughes, 2022) [88, 39] and games or interactive simulations. PBL is also a pedagogical approach in which students have to solve a problem (i.e. challenge), to overcome cognitive obstacles and reach a solution by integrating the solution of the decomposed initial problem to an overall solution (Xenakis *et al.*, 2023) [88]. Through problem-based scenarios, students learn how to solve a real-complex problem creatively. Infact, applying a wide range of alternative solutions to solve a problem, students come up with innovative ideas (Karamustafaoğlu *et al.*, 2023) [45]. PBL teaching intervention comprises of the following phases (Xenakis *et al.*, 2023) [88]: a) Concepts clarification and background information, b) Definition of Problem, c) Analysis, construction and solution planning, d) Application of the predominant solution, e) Work path definition as a function of the learning goals and f) Composition of the results, feedback and evaluation, as illustrated in Fig 9.

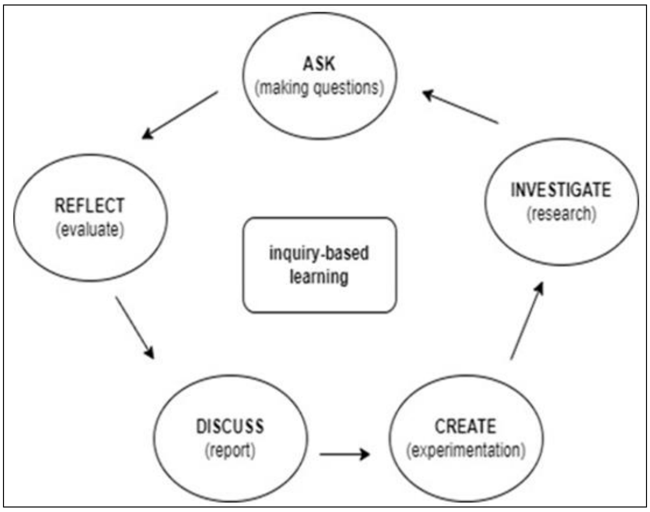

Fig 8: Steps of inquiry based learning

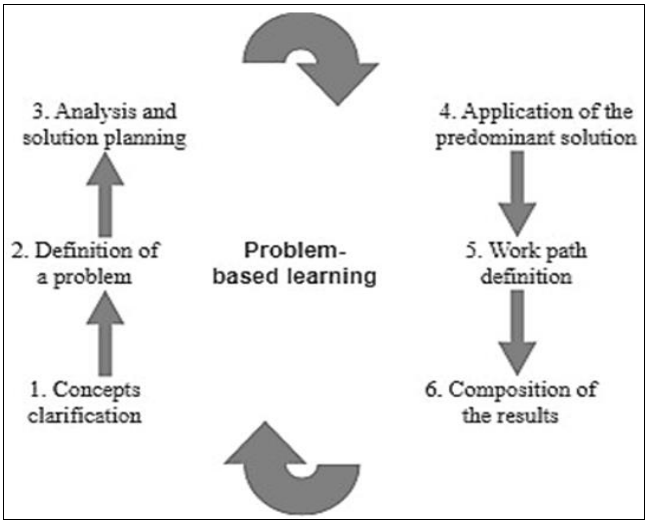

Fig 9: Phases of PBL

Project- Based learning (PjBL) is an experiential and student- centered learning approach which is often utilized in Science courses (Nordin *et al*., 2011; Saldo & Walang 2020; Prashanti *et al*., 2021; Hughes, 2022) [56, 74, 67, 39]. PjBL method is characterized as a constructivist pedagogy where students are exposed in real-world environments and hands-on activities in order to solve interdisciplinary problems (Samsudin & Jamali 2020) [75]. At the beginning, teachers choose a topic, i.e. "project-work" which leads to a problem scenario. Students are able to solve these problems by experimentations and observations. In fact, students discover lots of information and suggest several solutions about the problem called "project plans" by working in groups. Moreover, students collect their information about the problem scenario by conducting experiments, making observations, collecting data and record the results.

At the end of the session, each group of students present their results while they're evaluated by classmates and the teacher (Nurhidayah *et al*., 2021) [59]. PjBL model focuses on student's self-confidence, responsibility, cooperation and research skills. Lastly, the phases of PjBL model according to Nurhidayah *et al*. (2021) [59] are: 1) Reflection: Students relate their acquired knowledge to new one and start by identifying a problem scenario, 2) Research: Students collect data and information about the problem solution and discuss it with their team, 3) Discovery: Each group designs an experiment, 4) Application: Testing the experiment results and 5) Communication: Each group reports the results of their research, and draws conclusions together.

A learning method in which students' interest is increased by playing educational *serious games*, is the *Game- based* (Patiño *et al*., 2023) [64]. Quantum Serious games are interactive environments which are designed for a specific educational purpose. Also, pedagogical elements incorporate with these interactive simulations within motivation, fun and playful way (Piispanen *et al*., 2019) [69]. ***Game-based learning*** (GBL) involves designing and incorporating educational content within a game format, where players (i.e. students) actively participate and interact with the game mechanics to acquire basic knowledge (Videnovik *et al*., 2023) [82]. During GBL, students have fun with increased imagination and natural curiosity, which can lead to high levels of participation and the student's involvement in the learning process. In this way, students can be more engaged in meaningful learning, enhancing problem-solving, decision-making, and strategic planning skills.

Lately, in Science education, a technique which is often used for student's learning motivation, engagement and participation is ***gamification***. Specifically, gamification is the use of game-design elements, game-play mechanics, aesthetics and game-thinking into a non-game contexts e.g. online lesson sessions or academic courses (Kalogiannakis *et al*., 2021; Balci *et al*., 2022) [44, 9]. The main goal in gamification, is to alter a contextual learner behavior or attitude by carefully designed learning environments with clear instructions. Core parts of gamification could be game mechanics e.g. points, badges, storytelling or avatars which constitute the motivational power on students' learning process. A pedagogical model, which is used in Physics' courses is *flipped classroom* (Aşıksoy, 2018) [2]. In flipped classroom, the traditional lecture and homework elements of a course are reversed.

Particularly, students use a web based materials i.e. video lectures or podcasts outside of class time as a preparation for the in class course (Temporão *et al*., 2022 [80]; Davis, 2016). A category of flipped classroom approach is the ***just-in-time teaching pedagogy*** (JiTT) which is a web-based and pre-instruction assignment (i.e. warmups) where students complete online assignments such as reading, watching videos, doing exercises, or reporting difficulties they have had with the assignments before any formal classroom instruction (Novak, 2011) [62]. The Web materials which are added as a pedagogical resource, may also operate as a communication and organization tool. Consequently, teachers receive feedback from students and start a course with an awareness of the status of the class. The essence of JiTT pedagogy is the feedback loop structured by the students' preparation outside the classroom that reflect their in-class experience, as illustrated in Fig 10.

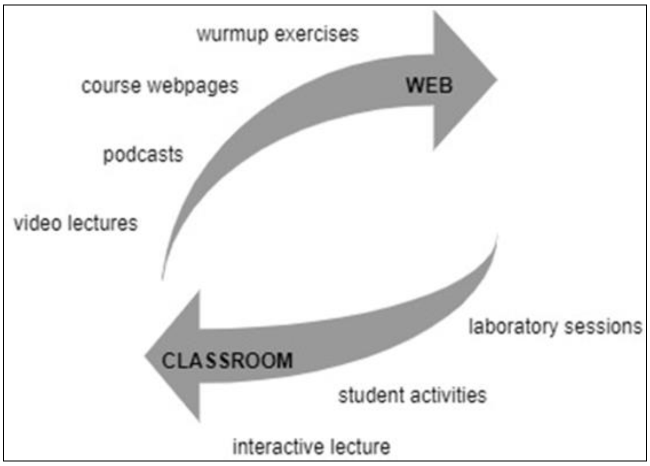

Fig 10: JiTT pedagogy process

2.3 Gamified Simulations for Quantum Knowledge

Recently, utilizing multimedia applications such as graphics, simulations, animations and videos in Science courses reinforce students' conceptual understanding, engagement and creativity. An experimental study which has been proposed by Nyirahabimana *et al*., (2023) [60] focuses on the impact of multimedia application on student conceptual understanding in Quantum Physics, resulting on a large statistical difference on learning outcomes among the two approaches (i.e. traditional and multimedia approach). Multimedia tools encourage students to connect mathematical formalism with physical reality of QP phenomena, improve their ability to solve physics problems, develop inference skills between physics and everyday life phenomena and enhance their creativity in verbal and figurative expression.

In the same context, an online course by including multimedia applications into a Quantum physic program contributed to foster lecture's quality with 70% passive level (Freericks, 2019) [30]. Also, teachers claimed that *"freely available digital materials were considered as an opportunity to support students' conceptual understanding as they have the potential to engage students and benefit their conceptual development"* (Bouchée *et al*., 2021) [10]. Quantum serious games (QSG) are designed for a specific educational purpose as tools of innovating the education process through a playground for scientific concepts that cannot be easily experimented (Anupam, 2018; Jankiewicz *et al*., 2022; Dorland, 2019; Aditya *et al*., 2020; Nita *et al*., 2020; Nita *et al*., 2021; Liu *et al*., 2023; Artner *et al*., 2023) [3, 42, 26, 5, 57, 58, 50, 6]. Quantum games, as an interactive environment, facilitates manipulation of system conditions and provides feedback to changes that students make through the system.

Also, pedagogical elements incorporate with serious games within motivation, fun and playful way (Foti *et al*., 2021; Piispanen *et al*., 2019) [32, 69]. Students' learning process is affected directly through instructional content of the game's environment (Kopf *et al*., 2023) [46] where players (i.e. students) actively participate and interact with game mechanics to enhance conceptual awareness, scientific-thinking or problem-solving skills (Nita *et al*., 2020) [57] without previous requirements. There are lots of categories of games such as video-games, board-games (Weisz *et al*., 2018) [85], puzzle-games and card-games which visualize the quantum world for quantum outreach and education practitioners (Chiofalo, 2021; Seskir, 2022) [12, 76].

John Preskill mentioned that "*perhaps kids who grow up playing quantum games will acquire a visceral understanding of quantum phenomena that our generation lacks*" (Preskil, 2018) [68]. Virtual laboratories consist of a graphical user interface which one can drag-and-drop nodes to create a flow-based simulation (Rodrigues, 2020; Jankiewicz *et al*., 2022) [72, 42] as for example: Quantum Composer (Aarhus University) and Phet simulator (University of Colorado). Using gamified virtual labs in quantum education, students can explore the probabilistic nature of quantum world through animated icons imitating the quantum mechanics or quantum computing concepts. Also, interactive simulations, provide an educational environment where students actively construct and acquire scientific concepts (Jankiewicz *et al*., 2022) [42]. In Table 1, we present the correlation between interactive gamified simulations and quantum learning topics as applied in quantum education. To be more specific, we present quantum games (in vertical axis) for teaching quantum superposition, quantum entanglement, quantum state, quantum measurement and quantum gates (in horizontal axis).

Table 1: Gamified interactive simulations for teaching quantum topics. Highlighted quantum games utilize inquiry-based and game-based didactic approaches and the rest of them utilize problem-based and game-based didactic approaches

QSG \ Learning Topics	quantum superposition	quantum entanglement	quantum state	quantum measurement	quantum gates
Entanglion *(Weisz, et al., 2018)* [85]	●	●	●	●	●
Quantum SG *(Heider et al., 2020)* [40]		●			
Particle in a Box *(Anupam et al., 2018)* [3]	●				
Psi and Delta *(Anupam et al., 2019)* [4]	●				
Hello Quantum *(Seskir et al., 2022)* [76]			●		●
Quantum Uno *(Seskir et al., 2022)* [76]	●	●		●	
Quantum Odyssey *(Nita et al., 2021)* [58]	●		●	●	●
Qupcakery *(Liu et al., 2023)* [50]	●		●	●	●
QRogue *(Artner et al., 2023)* [6]					●
Endless fun-Card Game *(Kopf et al., 2023)* [46]	●	●	●	●	●
Tangram Puzzle *(Patil et al., 2022)* [65]				●	●
Quantum TiqTaqToe *(Weingärtner, 2023)* [87]	●	●		●	
Quantum Battleship *(Casper & Grimes, 2023)* [20]		●		●	

Quantum Penny Flip *(Zapirain et al., 2019)* [89]	●		●		●
Quantum Go *(Ranchin, 2016)* [73]	●	●		●	
Qubit-Game *(Escanez-Exposito et al., 2023)* [27]		●	●		●
QuaSim *(Parakh et al., 2017)* [66]	●			●	
Q|Cards> *(Kerppo et al., 2019)* [49]					●
Quantum Chess *(Cantwell et al., 2019)* [24]	●	●		●	
Quantum Tapsilou *(Kastampolidou and Andronikos, 2023)* [43]		●			
Quantum Game with darts *(Ganti & Iyengar, 2023)* [34]			●	●	
Quantum Pocker *(Fuchs, 2019)* [33]			●	●	●
Quantum Minesweeper *(Gordon & Gordon, 2010)* [35]	●	●		●	
States and Gates *(Carberry et al., 2022)* [21]	●		●		●
Schrodinger cat & hounds *(Gordon & Gordon 2012)* [36]	●	●		●	
Quantum Blackjack *(Lin et al., 2020)* [52]		●			
Game for quantum measurement *(Corcovilos, 2018)* [23]				●	
Quantum Cats *(Cheung & Wallace, 2016)* [22]	●				
Quantum Minigolf *(Friedemann, 2010)* [31]		●	●	●	

3. Related Works

3.1 Teaching Methods for Basic Quantum Concepts

It is a fact that quantum technology will revolutionize the way we live, therefore quantum knowledge becomes a vital necessity for next generations, within Education 4.0 framework. Quantum education forms an opportunity and challenge where students learn how to engender creativity, experimentation and new ways of thinking behind real-world complex problems (Matsler *et al*., 2020; Edwards *et al*., n.d.) [53, 28]. At K-12 educational level, student's intuition of classical Physics principles, can be educated within classroom demonstrations of everyday life phenomena and mathematics suited to their instruction degree. However, in Quantum Physics, student's experience with phenomena of microscopic scale is limited and the mathematical framework is more appropriate for experts (Chiofalo *et al*., 2021) [12].

Consequently, various educational programs and activities have been developed for teaching basic quantum concepts in K-12 and undergraduate educational level (Pospiech, 2021; Montagnani *et al*., 2023; Heider *et al*., 2020; Satanassi *et al*., 2022; Vishwakarma *et al*., 2023) [70, 55, 40, 77, 83]. According to Montagnani *et al*., (2023) [55] an inquiry-based learning strategy has been proposed within experiments and a game experience for conceptual acquisition of basic quantum concepts. Students mentioned that "*the game-based activity helps to develop the ability of building intuition on quantum behavior, comprehending concepts like superposition and entanglement, and what distinguishes an entangled from an ordinary superposition state*".

Through inquiry-based teaching method, students are actively involved in the educational process, constructing, and acquiring basic scientific concepts within observation, investigation, and discovery (Walsh *et al*., 2022) [84]. IBL, is a student-centered didactic approach in which the learning process to scientific thinking is supported by making real world connections among problem-solving and experiential learning. An educational project within inquiry method, STEM related activities and gamification scenarios, has been proposed by (Xenakis *et al*., 2023) [88] reinforcing students' mathematical and computational - problem decomposition and modelling skills. Through problem-based and game-based learning technique, students also learned how to think behind quantum computational operations acquiring the basis for quantum knowledge.

Also, Walsh (2022) [84] presented an inquiry-based teaching method combined with a *just-in-time* teaching technique. As a consequence, students' programming skills and matrices have been reinforced essential to the educational framework and suitable for the conceptual awareness of quantum mechanics and computing concepts. Gamification is a teaching technique which facilitates scientific thinking within motivation, influences a learning- related behavior (Kalogiannakis *et al*., 2021) [44], engage students to the educational content and achieve better learning outcomes. Also, gamification could be as a key element into a teaching method (Aşıksoy, 2018) [2], in a web-based educational program (Katanosaka *et al*., 2022) [47] or in a real-live activity (Marckwordt *et al*., 2021; Lopez-Incera & Dür, 2019) [54, 51]. Learning requires the active participation of students within direct and interactive instruction, experiential learning, and independent study.

A gamified-flipped learning technique into a Physics course (Aşıksoy, 2018) [2] indicate the strong positive effect on the students' learning achievement and motivation. Through flipped classroom didactic model, teacher before lecture had to prepare digital, physical material and activities according to Physics course as preparatory work of the student's out-of-class through technology. Following, students had to prepare the theoretical part of the course on their own pace in order to increase the quality time of the physical course focusing on the application of the acquired knowledge (Toriz, 2019; Aşıksoy, 2018) [79, 2]. Also, badges, points and leaderboards framed by flipped learning techniques can increase students' competition, motivation, active participation in the class fostering the whole learning process (Aşıksoy, 2018) [2]. To conclude, in Table 2 we summarize contemporary didactic approaches as applied in the teaching process of basic quantum knowledge.

Table 2: Related works on teaching methods for basic quantum concepts

Didactic approaches	Learning topics	Ref.
IBL, PBL, GBL	quantum superposition, quantum gates: H, X, CNOT quantum entanglement	*(Xenakis et al., 2023)* [88]
IBL, GBL	quantum superposition, quantum entanglement, quantum state, quantum measurement	*(Montagnani et al., 2023)* [55]
PjBL, GBL	quantum state, quantum superposition, quantum measurement, quantum gates: H, X, CNOT quantum entanglement	*(Prashanti et al., 2021)* [67]
PjBL, GBL, PBL	quantum superposition, quantum measurement, quantum entanglement	*(Hughes et al., 2022)* [39]
IBL, JiTT	quantum state, quantum gates	*(Walsh et al., 2021)*
GBL	quantum entanglement	*(Marckwordt et al., 2019)*
PjBL, GBL	quantum state, quantum superposition, quantum entanglement, quantum measurement	*(Chiofalo et al., 2022)* [13]
PjBL, GBL	quantum superposition, quantum gates: SWAP, CNOT, H, X	*(Economou, 2020)* [29]
IBL, GBL	quantum superposition, quantum entanglement, quantum measurement	*(Gaunkar, 2024)* [37]

3.2 Evaluation of Quantum Games for Basic Quantum Topics

Evaluating quantum learning topics involves assessing various aspects such as content, pedagogy, and game effectiveness (e.g. engagement, assessment and feedback). According to Chiofalo *et al*., (2022) [13]; Gordon *et al*., (2012) [36]; Escanez-Exposito *et al*., (2023) [27]; Anupam *et al*., (2018) [3]; Liu *et al*., (2023) [50] it is noticeable that the contribution of quantum games to students' learning outcomes have positive effect. A research which has been conducted by Chiofalo *et al*., (2022) [13] point out that many students within quantum games clarified misconceptions about basic quantum topics such as quantum measurement, quantum superposition and entanglement. In the same context, Gordon *et al*., (2012) [36] increase students' learning effects by utilizing a quantum game for teaching basic quantum concepts. It is important to say that the concept of quantum entanglement seems to be one of the most difficult-to grasp-concept among others, thus students would like to be explained further (Chiofalo, 2022; Gordon, 2012) [13, 36].

The concept of quantum entanglement might be difficult to acquire due to several reasons such as its complexity, lack of direct observation or interpretations of this concept among others (e.g. non-locality concept). On the topic of quantum gates, Escanez-Exposito *et al*., (2023) [27] and Liu *et al*., (2023) [50] come to the conclusion that quantum games have been minimized several difficulties around quantum computing concepts and how to use quantum gates properly in gamified problem-based scenarios. In fact, students within quantum games were able to acquire the essential concepts of quantum computing (Escanez- Exposito, 2023) [27]. Finally, there are plenty of quantum games which indicate positive results in students' engagement and learning experience (Weisz, 2018; Anupam 2018; Nita, 2021) [85, 3, 58]. Nevertheless, in related studies the results among the evaluation of quantum learning topics and quantum games are limited so we cannot elicit further information (Seskir, 2022) [76].

4. Discussion - Research Findings

4.1 Quantum Games and Basic Quantum Topics

In Fig 11, we highlight the trend emerging, as to which basic quantum topics relates to the number of interactive quantum games. In this section, we summarize information from Table 1 and in particular we show that;

- 41% of quantum games (i.e. 12/29) have been developed for teaching **quantum gates** to students. Quantum gates are the practical realization of the fundamental principles of quantum mechanics applied to quantum computing. In fact when students learn how to use properly Hadamard gate into a quantum circuit they also become familiar with quantum superposition and measurement concept.
- 55% of quantum games (i.e. 16/29) have been developed for teaching **quantum superposition** and 48% (i.e. 14/29) for teaching **quantum entanglement**. According to the trend of quantum gates, the concepts of quantum superposition and entanglement own high rate development into quantum games. These two fundamental concepts play crucial and prominent role in the functioning and effectiveness of quantum gates and quantum computing in general.
- 58% of quantum games (i.e. 17/29) have been developed for teaching **quantum measurement**. Due to the highest rate of quantum measurement into quantum games, this fundamental concept comprises the function of all quantum gates into quantum circuits. Also, the trend of quantum measurement complies with the philosophy of quantum games and problem solving scenarios that students have to solve into gamified environments (Fig 12).
- 37% of quantum games (i.e. 11/29) have been developed for teaching **quantum state**. It is a fact that, the concept of quantum state is close enough to the concept of quantum measurement. In essence, teaching quantum measurement requires students' perceiving of the state of a quantum system (e.g. qubit) in order to measure it. Additionally, in corresponding literature, we often come across with the term of *decoherence* which is a connection of these two concepts. Unfortunately, there is limited information for the development of quantum state as a discrete concept into quantum serious games.

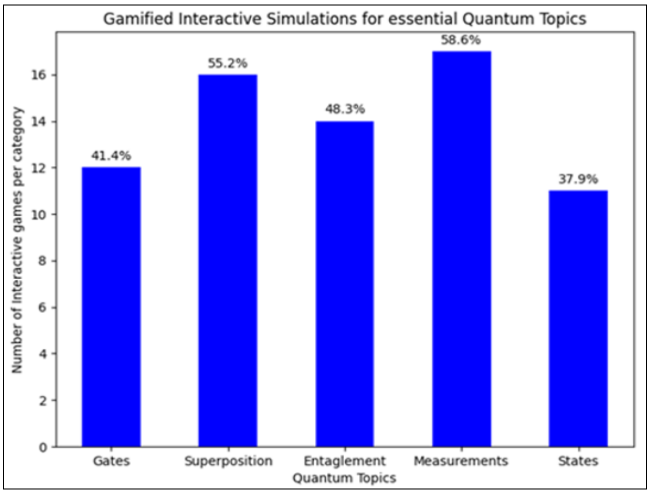

Fig 11: Tendency of quantum topics into gamified interactive simulations

Overall, according to Fig 11, we see that superposition and measurement concept have the highest rate as we expected for. We claim that the trends of these two quantum topics correlate with the philosophy of the Spin First approach through the analysis of sequential *Stern-Gerlach* spin experiments with discrete two state spin-half bases. Through this approach students can firstly focus on abstract concepts while the mathematics are simple and limited to two discrete states. In more details, students can grasp the concept of *quantum measurement* within calculations in Hilbert spaces using the Bloch sphere and Bloch vectors. Also, aligning the spin-half with other two state systems such as qubit, students also can learn about the concept of *quantum superposition*, which is a key to many applications.

4.2 Quantum Games and Didactic Approaches

According to Table 1, the didactic approaches that have been used into quantum serious games are: *Game-based learning, inquiry-based learning and problem-based learning* as depicted in Fig 12. In more details:

- 20% of quantum games (i.e. 6/29 which have been highlighted in Table 1) have been developed utilizing **game-based learning and inquiry-based learning** didactic approaches. Students' goal is the conceptual learning of basic quantum concepts by comparing the similarities and differences between quantum physics and classical physics (Seskir, 2022) [76]. Also, students have to recognize the notions of basic quantum concepts within game - based learning techniques (Carberry, 2022) [21]. Finally, learning goals have been evaluated through questionnaires focusing on quantum topics (i.e. quantum superposition, quantum entanglement, quantum measurement, quantum states and quantum gates)
- 80% of quantum games (i.e. 23/29) have been developed utilizing **game-based learning and problem-based learning** didactic approaches. Students' goal is the conceptual learning of basic quantum concepts by solving gamified problem - based scenarios. In fact, students engage in problem solving scenarios to find solutions within a strategic role of thinking i.e. computational thinking (Weisz, *et al.*, 2018) [85]. Also, students have to manipulate game mechanics, utilizing game's quantum rules (Parakh, 2017; Weingärtner, 2023; Weisz, 2018; Liu, 2023) [66, 87, 85, 50].

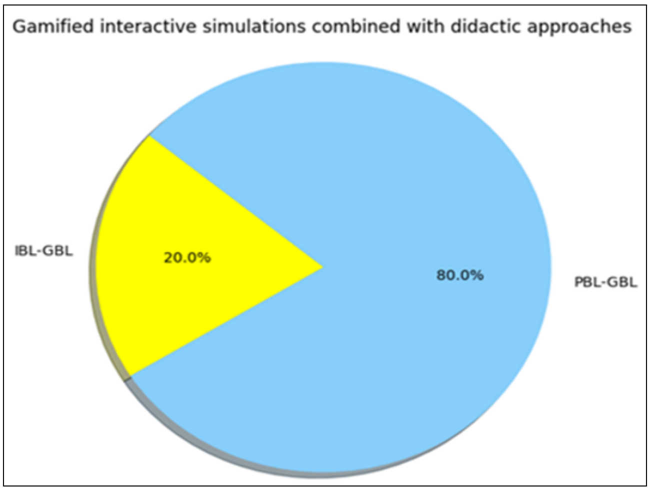

Fig 12: Tendency of didactic approaches into quantum games

Moreover, Table 1 highlights the connection between quantum games, quantum learning topics and contemporary didactic approaches. For example, quantum superposition can be taught through the game Quantum Odyssey utilizing problem-based and game-based didactic approaches and quantum measurement within the game States and Gates utilizing inquiry-based and game-based didactic approaches. Also, the majority of quantum games can foster the development of computational thinking ability within quantum problem-solving scenarios, in which students need to understand and leverage the unique properties of quantum systems to solve gamified problems. Xenakis *et al* (2023) [88], Weisz, J (2018) [85] point out that computational thinking (CT) is a thought process in which problems and solutions are formulated in ways that align with how computers work. It's about breaking down problems into smaller, more manageable parts, and then using a logical and systematic approach to analyze and solve them. CT involves problem-solving techniques such as abstraction, simulation, pattern recognition, algorithm design, and the ability to think recursively. Like classical CT, quantum computational thinking (QCT) involves breaking down problems into smaller components, designing algorithms to solve these components efficiently and considering the resources available in a quantum computing system to achieve the desired outcomes.

QCT is a multifaceted CT at the nexus of science, engineering and computation, which comprises of the following additional pillars: A **scientific ability** to think in terms of quantum mechanics, an **engineering ability** to apply quantum mechanics to solve computation problems and a **computational ability** to use CT to process quantum information (Xenakis, 2023) [88]. Quantum games can be a valuable tool for building QCT skills in students (Weisz, *et al.*, 2018) [85]. As depicted in Fig 12, 80% of quantum games within problem solving scenarios and a PBL didactic approach, can enhance QCT skills in students. Quantum games also, provide interactive and engaging environments where players can learn about quantum concepts and principles while solving puzzles or completing challenges. By presenting quantum phenomena in a gamified format, students can develop an intuitive understanding of quantum mechanics and quantum computing concepts. Moreover, quantum games can help make complex topics more accessible and enjoyable for students, encouraging them to explore and experiment with quantum concepts in a low-pressure environment. This hands-on approach can complement traditional teaching methods and enhance students' understanding of QCT.

5. Conclusions

In this work we map the State-of-the-art correlation among contemporary teaching methods and gamification techniques and tools, as applied for quantum mechanics concepts and quantum computing problems, to best advance QL. We also discuss the trends among contemporary teaching methods and effective gamification tools, fostering quantum physics knowledge in K-12 educational level. Results saw that among quantum superposition, quantum entanglement, quantum measurement, quantum state and quantum gates, the concepts which have been developed by most of quantum games were superposition and entanglement. This result comes to an alignment with the Spin First approach which is often used as an introductive learning approach of basic Quantum Mechanics concepts. Also, we notice that few quantum games provide information about teaching quantum state as a discrete concept something that has to be further developed.

Moreover, we indicate a connection between quantum games, quantum learning topics and contemporary didactic approaches. The didactic approaches utilized by most of quantum games are game-based learning and problem-based learning. Consequently, 80% of quantum games tend to foster problem-solving and quantum computational skills among students. This result highlights that the general trend of quantum games is not only the conceptual acquisition of quantum concepts but also the application of quantum mechanics and quantum computing concepts into solving scenarios i.e. puzzles or completing challenges. Lastly, there are limited research findings in evaluation of quantum games in teaching process.

6. Authors' contributions

All authors were involved in preparing this manuscript and have provided significant intellectual input. All authors read and approved the final manuscript.

7. Disclosure statement

No potential conflict of interest was reported by the author(s).

8. Ethics statement

This paper is a survey of existing literature and data from previously published sources. All relevant data and sources are appropriately cited within the text.

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