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Scaffolding quantum entanglement in secondary school: from tangible analogy to computational simulation

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Background and purpose of the study: The rise of quantum technologies necessitates integrating foundational quantum mechanics (QM) concepts into secondary education. However, inherently abstract phenomena like quantum entanglement pose significant pedagogical challenges, as traditional formalism-based approaches are often inaccessible. This study introduces and delineates an innovative, scaffolded pedagogical model designed to foster robust conceptual understanding of entanglement in secondary STEM education, moving beyond reliance on mathematical formalism.

The proposed pedagogical model: The presented contribution is a detailed pedagogical sequence following a deliberate learning trajectory. It begins with a tangible analogy (magnetic interactions) as a conceptual anchor for correlation, then transitions to computational tools (Bloch sphere visualization, Qiskit simulations). These tools facilitate exploration of quantum concepts weakly addressed by the analogy (e.g., superposition) and allow more authentic engagement with quantum behavior. Underpinned by constructivism, cognitive load theory, and QM education research, the model strategically repurposes the analogy's limitations as pedagogical opportunities to introduce and contrast key quantum features like non-locality and superposition with classical intuition. The sequence integrates exploration, guided use of representations, and critical comparative discussion.

Conclusions and potential implications: This paper provides a theoretically grounded pedagogical model for introducing quantum entanglement in secondary STEM education, combining tangible and computational tools in a scaffolded manner. The approach offers potential advantages over traditional methods by providing concrete starting points and explicitly using classical limitations to illuminate quantum principles. While promising, rigorous empirical validation is the essential next step. Future research should investigate the model's effectiveness in authentic classroom settings, informing curriculum design and teacher development for incorporating QM into secondary STEM.

KEYWORDS

Bloch sphere, computer simulation, constructivism, didactic proposal, learning difficulties, magnetic analogy, physics teaching, Qiskit

1 Introduction

1.1 The pedagogical imperative and challenges of quantum mechanics in the 21st century

The 21st century marks the rise of the quantum technology era, with quantum mechanics (QM) evolving from an abstract theoretical framework into the foundation for revolutionary scientific and industrial advancements, from quantum computing to intrinsically secure communication (Hossain, 2023; How and Cheah, 2024). This profound paradigm shift creates an urgent educational need, aligning with Sustainable Development Goal 4 (SDG 4, which calls for inclusive and equitable quality education and lifelong learning opportunities for all) by fostering essential scientific competencies and promoting innovation relevant to SDG 9, to equip secondary-level students with foundational quantum literacy (Pelton and Madry, 2023; Nita et al., 2021). Such literacy, understood here as possessing a conceptual grasp of core quantum principles and appreciating their stark departure from classical physics—sufficient for informed citizenship and future learning pathways—is required for meaningful participation in tomorrow's technological landscape (Doyle, 2023; Steen, 2004). However, teaching QM effectively at this level remains a significant challenge (Bouchée et al., 2021a), compounded by the fact that secondary students are typically consolidating abstract reasoning skills while holding strong, potentially interfering, intuitions derived from prior classical physics instruction. Physics education research (PER) consistently documents persistent, deep-rooted student difficulties with core QM concepts, particularly the complex phenomenon of quantum entanglement, where learners often default to classical interpretations despite targeted instruction (Brundage et al., 2025; Majidy, 2024; Nikolaus et al., 2024). These challenges are amplified by the tension inherent in conventional pedagogical approaches: the recognized inaccessibility of mathematical formalism for many secondary students (Lovisetti et al., 2024; Tóth et al., 2024) versus the risks of oversimplified qualitative models, which can materially distort essential quantum phenomena (Keebaugh et al., 2024; Zuccarini and Malgieri, 2024).

Quantum entanglement clearly illustrates this pedagogical challenge (Irvani et al., 2024; Majidy, 2024). Described by Einstein as “spooky action at a distance,” its manifestation of non-local correlations fundamentally defies classical notions of causality and locality (Grossi et al., 2024). Empirical studies within PER consistently show that, even after instruction, students often misinterpret entanglement using classical ideas, such as pre-existing classical correlation or localized hidden-variable dependencies (Bao et al., 2022; Brang et al., 2024; Bøe et al., 2018; De Ambrosis and Levrini, 2010; Krijtenburg-Lewerissa et al., 2017). This highlights the critical need for novel instructional strategies designed to: (1) avoid deep mathematical abstraction while preserving conceptual accuracy; (2) systematically address classical intuitions through targeted cognitive conflict; and (3) scaffold understanding using carefully sequenced multimodal representations.

To address these requirements, the present paper introduces a novel, research-based pedagogical model that strategically bridges tangible analogy with accessible, yet powerful, computational tools. Informed by constructivist learning principles and cognitive load theory (Zambrano et al., 2019; Song et al., 2023), the model progresses

systematically through distinct phases explicitly designed to manage cognitive load by carefully scaffolding complexity. First, it employs a concrete analogy based on magnetic dipole interactions—chosen for its potential to offer an intuitive, tangible anchor for visualizing correlation phenomena—as an initial conceptual entry point. Second, acknowledging the inherent limitations of any classical analogy for capturing uniquely quantum effects, it transitions to interactive computational simulations—specifically employing activities based on the Qiskit framework alongside Bloch sphere visualizations—to facilitate exploration of superposition and non-locality, concepts extending beyond the analogy's representational capacity. Finally, this structured sequence culminates in guided conceptual mapping exercises designed to explicitly contrast classical versus quantum behaviors without reliance on advanced mathematical formalism, thereby promoting the construction of accurate mental models.

This work offers several distinct contributions to the field. First, it establishes a coherent theoretical framework for entanglement instruction that balances conceptual accessibility with quantum authenticity. Second, it presents a reproducible, adaptable instructional sequence featuring research-based analogy implementation, the use of accessible computational tools (requiring only standard web browser access), and explicit conceptual differentiation activities. Finally, through its articulated scaffolded design principles, the model offers a potentially generalizable template applicable to similarly challenging topics within QM education.

While comprehensive empirical validation is necessary future work, this article provides a rigorous justification for the design choices, grounded in established PER findings and contemporary learning theories. It offers adaptable implementation guidelines suitable for diverse classroom contexts and proposes a preliminary framework for assessing the pedagogical efficacy of analogy-simulation integration strategies within broader STEM education.

The structure of the present manuscript progresses logically as follows. In the Introduction, we synthesize relevant Physics education research literature regarding established student misconceptions about the complexities of quantum entanglement. In (1) Background and Theoretical Foundations, the theoretical principles underpinning the proposed pedagogical model are elaborated. In (2) Proposed Didactic Sequence, the core didactic design is presented in detail, illustrated with concrete classroom examples. In the Discussion, we critically address the model's limitations alongside its broader pedagogical and research implications. Finally, in the Conclusion, we outline salient directions for future empirical investigation and iterative refinement of the pedagogical approach.

While several studies have explored student's conceptions of quantum phenomena and proposed instructional approaches to modern physics, few have specifically addressed entanglement in secondary education. Existing interventions often rely either on simplified qualitative models (e.g., glove analogies) or on advanced mathematical formalism, which limits accessibility for younger learners. In contrast, the present design introduces a distinctive combination of features: the use of magnetic dipole interactions as a tangible analogy familiar to secondary students, the explicit pedagogical linkage between this analogy and computational simulations (Bloch sphere visualizations and Qiskit circuits), the carefully scaffolded sequencing of activities designed to manage cognitive load and highlight the breakdown points of the analogy, and the focus on upper secondary students (16–18 years old), a population

rarely targeted in prior entanglement interventions. This combination differentiates the present work from related studies (e.g., [Batle et al., 2017](#); [Paneru et al., 2020](#); [Michelini and Stefanel, 2023](#)) and provides a novel, age-appropriate trajectory that integrates tangible and digital tools within a coherent constructivist framework. To guide the study and ensure coherence across the subsequent sections, the following research questions are posed: (1) How does secondary student's conceptual understanding of quantum entanglement evolve throughout a didactic sequence based on tangible analogies and computational simulations? (2) What role do analogies and simulations play in the construction of accurate mental models of quantum phenomena, compared to students' prior classical intuitions? (3) In what ways does the proposed sequence contribute to managing cognitive load and fostering meaningful learning of quantum concepts in a school context?

In order to provide a clear focus and ensure coherence across the subsequent sections, the study is guided by a set of explicit research questions. These questions articulate the central aims of the work and serve as the framework for structuring the methodology, analysis, and discussion.

Research questions:

- (1) How does secondary students' conceptual understanding of quantum entanglement evolve throughout a didactic sequence based on tangible analogies and computational simulations?
- (2) What role do analogies and simulations play in the construction of accurate mental models of quantum phenomena, compared to students' prior classical intuitions?
- (3) In what ways does the proposed sequence contribute to managing cognitive load and fostering meaningful learning of quantum concepts in a school context?

2 Background and theoretical foundations

The teaching and learning of quantum mechanics (QM) present unique challenges, widely documented within the science education literature ([Bitzenbauer, 2021](#); [Bouchée et al., 2021a](#); [Perron et al., 2021](#); [Tóth et al., 2024](#)). These difficulties largely stem from the counterintuitive nature of quantum phenomena, which often contradict everyday experience and the principles of classical physics; quantum entanglement serves as a prime example of this stark departure ([De Ronde, 2023b](#); [Chiarelli and Chiarelli, 2024](#)). This section first analyzes the primary conceptual hurdles students face, particularly concerning quantum entanglement, before reviewing the pedagogical tools and learning theories that inform the instructional model proposed in this paper.

2.1 Learning difficulties in quantum mechanics

Physics education research (PER) has consistently identified significant conceptual obstacles hindering students' understanding of QM ([Majidy, 2024](#); [Serbin and Wawro, 2024](#)). These difficulties persist from secondary school through university physics ([Bouchée et al., 2021b](#); [Krijtenburg-Lewerissa et al., 2017](#)) and contribute significantly

to the high intrinsic cognitive load associated with the subject. Among the key areas particularly relevant to the challenges addressed in this paper is quantum superposition ([Krijtenburg-Lewerissa et al., 2017](#); [Michelini and Stefanel, 2023](#); [Weissman et al., 2022](#)). Grasping this foundational principle—that a particle can exist in multiple states simultaneously until measured ([De Ronde, 2023a](#))—is deeply challenging, particularly for secondary students who are often still consolidating formal abstract reasoning skills. Accustomed to classical objects having definite properties, students often misinterpret superposition as a statistical mixture or simple epistemic uncertainty (lack of knowledge) rather than recognizing it as an intrinsic ontological property ([Zuccarini and Malgieri, 2024](#)), thereby hindering comprehension of phenomena like quantum interference. Perhaps even more counterintuitive, and central to this work, is entanglement. This concept refers to the non-local correlation between two or more quantum systems, where their states remain linked regardless of separation ([Jaeger, 2014](#)). Such correlation, experimentally verified to violate Bell inequalities ([Barr et al., 2024](#)) and inexplicable by local hidden variables, represents a stark conflict with the principles of locality and causality emphasized in prior classical physics education. Consequently, students often attempt to impose classical causality or misinterpret entanglement as merely strong classical correlation, akin to the separated gloves analogy ([Batle et al., 2017](#); [Paneru et al., 2020](#)), failing to grasp its fundamental non-locality.

Compounding these issues related to state description is the nature of quantum measurement. The measurement process fundamentally differs from classical observation; it actively alters the quantum state through a probabilistic “collapse” of the wave function ([Morgan, 2022](#); [Wong, 2024](#)). Students grapple with the observer's role, the inherent probabilistic nature, and the counterintuitive idea that measurement can define reality rather than merely revealing pre-existing properties ([Bouchée et al., 2021b](#); [Huseby and Bungum, 2019](#))—concepts demanding a level of abstraction that is challenging for learners solidifying formal operational thought. Furthermore, wave-particle duality challenges classical intuition. The notion that quantum entities exhibit both wave and particle properties ([Hobson, 2024](#)) often conflicts with the distinct categorical thinking reinforced in earlier science education, leading students to attempt inappropriate classical framings like imagining particles “switching” between states ([Onorato et al., 2024](#)), which obstructs understanding of phenomena such as electron diffraction.

Layered upon these conceptual challenges is the mathematical formalism of QM. The sophisticated mathematics involved (linear algebra, complex numbers, Hilbert spaces) represents a significant barrier, especially for secondary students ([Pospiech et al., 2021](#); [Schermerhorn et al., 2022](#); [Serbin and Wawro, 2024](#)), often precluding access to deeper conceptual understanding *via* traditional instruction.

Addressing these deep-seated difficulties, which impose high cognitive demands and clash with established classical frameworks, necessitates pedagogical approaches that move beyond formalism and directly engage with students' conceptual frameworks, employing strategies designed to manage cognitive load and facilitate conceptual change, particularly regarding superposition and entanglement.

Several recent initiatives have attempted to introduce quantum mechanics at the secondary level by emphasizing accessible representations and reducing the reliance on advanced mathematical formalism. For instance, [Syafitri et al. \(2024\)](#) explored the introduction

of step and barrier potentials to Class X students in Indonesia, demonstrating that carefully designed activities can make abstract quantum systems approachable without sacrificing conceptual accuracy. This aligns with our approach of combining tangible analogies and computational simulations to scaffold students' reasoning about entanglement.

2.2 The role and challenges of analogies in QM education

Faced with the significant conceptual and abstract challenges documented in QM learning (Section 2.1), the use of analogies becomes a particularly attractive, yet inherently complex, pedagogical strategy in science education (Bouchée et al., 2021a, 2021b; Nita et al., 2021). Analogies map features from a familiar domain (the analog) to an unfamiliar target concept (Angara et al., 2022; Bouchée et al., 2021b), potentially making abstract ideas more accessible by leveraging existing knowledge (Cruz-Hastenreiter, 2015; Michelini and Stefanel, 2023; Zuccarini and Malgieri, 2024). However, the profoundly non-classical nature of QM demands exceptional care in their application.

Realizing the potential of analogies requires careful pedagogical design, as their effectiveness is context-dependent and misuse can inadvertently foster misconceptions (Krijtenburg-Lewerissa et al., 2017; Mammino, 2023). Not all analogies are equally effective, and poorly chosen or implemented ones can readily lead to further confusion. Influential frameworks, such as the Teaching-With-Analogies (TWA) model (Didiș, 2015; Cruz-Hastenreiter, 2015), provide pedagogical guidance, emphasizing the critical need for systematic mapping of shared attributes alongside explicit instruction regarding the analogy's inevitable limitations or 'breakdown points'. In line with such frameworks, effective analogies should ideally share relevant structural attributes with the target, be familiar and concrete to the learner, and crucially, have their limitations explicitly acknowledged and discussed (Mammino, 2023; Pospiech et al., 2021; Zuccarini and Malgieri, 2024).

Ignoring these limitations is a well-known risk, potentially leading students to overgeneralize the analogy and form erroneous conceptions (Mammino, 2023), such as incorrectly inferring that light needs a medium based on water wave analogies (Lewis et al., 2021). Consequently, effective analogical reasoning in QM requires careful planning, explicit mediation by the instructor, and strategies for addressing the inevitable points where the analogy breaks down (Cruz-Hastenreiter, 2015), potentially leveraging these breakdown points themselves as opportunities to highlight unique quantum features (Didiș, 2015). Recognizing these potentials and pitfalls informs the structured use of the magnetic analogy within the proposed sequence (Section 3).

2.3 Leveraging visualizations and simulations

Functioning synergistically with analogies, computational visualizations, and interactive simulations have garnered recognition as valuable pedagogical instruments within conceptually demanding physics domains such as quantum

mechanics (QM) (Krijtenburg-Lewerissa et al., 2017; Theodoropoulou et al., 2024; Weber and Wilhelm, 2020). These tools afford representation of phenomena inaccessible to direct sensory experience due to constraints of scale, temporality, or inherent abstraction (Ahmed et al., 2021; Zuccarini and Malgieri, 2024). Judiciously designed computational instruments confer multiple pedagogical advantages for student learning. Primarily, they augment conceptual understanding through the visualization of otherwise unobservable phenomena; microscopic processes like electron behavior or abstract qubit state dynamics become visually accessible, cultivating deeper conceptual intuition (Angara et al., 2022; Kaushik et al., 2023). This visualization capability enables learners to cultivate an intuitive grasp of system behavior, potentially even absent comprehensive mastery of the attendant mathematical formalism (Krijtenburg-Lewerissa et al., 2017; Lovisetti et al., 2024). Furthermore, simulations possess the capacity to bridge abstract theoretical constructs with more concrete representational forms, for instance, employing geometric representations like the Bloch sphere to depict abstract qubit states and processes such as superposition (Pospiech et al., 2021; Theodoropoulou et al., 2024).

Beyond mere visualization, these computational tools foster active learning *via* interactive exploratory engagement. By permitting students to dynamically manipulate system parameters and observe immediate consequences, simulations enable exploration of hypothetical "what if" scenarios, aligning fundamentally with constructivist learning paradigms (Sun et al., 2024; Patterson and Ding, 2025). Such interaction directly facilitates learners' construction, testing, and refinement of their mental models concerning the phenomena under investigation. From a cognitive standpoint, visualizations and simulations can be designed to mitigate cognitive load. Rendering intricate information *via* visual and interactive modalities can potentially diminish extraneous cognitive load (Hennig et al., 2024; Nita et al., 2021), thereby liberating critical cognitive resources for more substantive conceptual processing and durable understanding (Ahmed et al., 2021; Weissman et al., 2022).

However, akin to analogies, computational simulations are not without inherent limitations. They inevitably constitute simplified abstractions of physical reality, and their pedagogical efficacy is contingent upon student prior knowledge and, critically, upon the instructional guidance orchestrated by the educator (Lovisetti and Giliberti, 2023; Pospiech et al., 2021) a consideration explicitly addressed through the guided activities and structured discussion prompts integral to the proposed pedagogical sequence (Section 3). Effective implementation necessitates instructors guiding students to navigate and interpret the visual outputs, integrate these representations with underlying theoretical concepts, and critically recognize the simulation's operational scope and intrinsic simplifications (Majidy, 2024). Specifically, within the challenging context of quantum entanglement, the strategic amalgamation of a concrete analogy with carefully selected simulations (such as Qiskit circuits visualized *via* the Bloch sphere) presents a potent synergistic instructional approach. The analogy furnishes an accessible conceptual entry point, whereas the simulation facilitates exploration transcending the analogy's intrinsic boundaries (e.g., enabling a more faithful visualization of phenomena like superposition) and furnishes a conceptual bridge towards more formalized quantum descriptions, as implemented in Section 3.

2.4 Guiding principles: learning theories

To effectively integrate analogies and simulations (Sections 2.2, 2.3) in addressing the learning difficulties identified earlier (Section 2.1), the design of the proposed pedagogical sequence is explicitly grounded in established learning theories.

The first guiding framework is Constructivism, which posits that learners actively construct knowledge based on prior experiences and new information (Patterson and Ding, 2025), rather than passively receiving it. Perspectives ranging from individual constructivism, emphasizing assimilation and accommodation processes (Nautiyal et al., 2025; Steffe and Ulrich, 2020), to social constructivism, highlighting the role of interaction within the Zone of Proximal Development (Al-Kamzari and Alias, 2025; Shrestha et al., 2023), inform the proposal. Accordingly, the pedagogical sequence is designed to promote active learning through interaction with the analogy and simulations, explicitly connects to students' prior knowledge of relevant concepts like magnetism and probability, guides meaning construction *via* exploration rather than direct transmission, and incorporates opportunities for social interaction through group work and structured discussions.

The second guiding framework is Cognitive Load Theory (CLT), which focuses on the limitations of human working memory during learning (Gkintoni et al., 2025; Pengelley et al., 2024; Tarnag and Pei, 2023). CLT suggests that effective instruction should minimize extraneous load (related to how information is presented) and manage intrinsic load (inherent complexity of the learning material), while actively fostering germane load (associated with deep processing and schema construction). The proposal aims to manage cognitive load *via* several integrated strategies. First, using a concrete analogy seeks to reduce intrinsic load when introducing abstract quantum concepts. Second, employing visualizations, such as the Bloch sphere and simulation outputs, helps offload working memory demands. Third, implementing careful scaffolding guides learners by sequencing content progressively from familiar to complex. Additionally, segmenting the complex topic of entanglement into more manageable conceptual parts further controls intrinsic load. Furthermore, providing explicit guidance through clear instructions and teacher support is intended to minimize extraneous load. Finally, germane load is fostered by designing activities—particularly the comparative analysis between analogy and simulation and the conceptual mapping exercises detailed in Section 3—that require students to invest cognitive effort in building accurate schemas and contrasting classical versus quantum models.

Applying these complementary theories aims to create an effective learning environment where students can efficiently utilize their limited cognitive resources for the meaningful construction of challenging QM concepts.

2.5 The chosen analogy: magnetic dipoles

Guided by the theoretical principles outlined above (Section 2.4), the proposed pedagogical sequence (Section 3) utilizes an analogy based on the interaction of magnetic dipoles (bar magnets) as a tangible starting point for the concept of correlation inherent in entanglement. This analogy was chosen for its familiarity and concreteness for secondary students. Its primary pedagogical function

within the sequence is to provide an intuitive, physical anchor for the idea that the state of one part of a system can be perfectly correlated with the state of another. However, as emphasized by research on analogies (Section 2.2), recognizing its limitations is crucial. Key limitations, such as its classical nature, reliance on local interactions, and inability to faithfully represent quantum superposition, are explicitly addressed not as mere flaws, but are leveraged pedagogically within the sequence (detailed in Section 3) as contrast points to introduce and highlight the uniquely non-classical features of quantum entanglement. A detailed analysis of the specific correspondences and limitations is integrated into the description of the didactic sequence (Section 3) where these points are actively discussed with students.

2.5.1 Design and limits of the analogy

The magnetic dipole analogy was deliberately chosen to provide students with a familiar and tangible entry point into the idea of correlation. Specifically, the analogy is intended to capture the notion of non-classical correlations, where the state of one system is linked to the state of another, and to highlight the impossibility of explaining such correlations purely through local classical mechanisms. However, several aspects of entanglement are intentionally simplified or omitted. The analogy does not represent non-locality in its full quantum sense, nor does it capture the role of superposition or the impossibility of hidden-variable explanations. These omissions are not treated as flaws but as pedagogical opportunities: the teaching sequence explicitly guides students to recognize where the analogy breaks down. For example, while magnets interact through local forces, entangled quantum systems exhibit correlations that persist across spatial separation without any mediating signal. Classroom discussions and comparative activities are structured to make these breakdown points explicit, prompting students to contrast the classical behavior of magnets with the quantum behavior observed in simulations. This transition from tangible analogy to computational representation is designed to scaffold students toward more abstract reasoning, enabling them to appreciate the uniquely non-classical features of entanglement.

3 Proposed didactic sequence: scaffolding introduction to quantum entanglement

This section details an innovative five-phase didactic sequence designed to introduce the complex topic of quantum entanglement to secondary physics students (approximately 16–18 years old) with foundational knowledge in classical physics (mechanics, EandM basics) and basic probability. The sequence integrates constructivist principles (Al-Kamzari and Alias, 2025; Lovisetti et al., 2024; Nautiyal et al., 2025; Weissman et al., 2022) and collaborative learning strategies (Brundage et al., 2023; Rasjid and Bahar, 2023; Rodriguez et al., 2020), and is meticulously designed to manage intrinsic and extrinsic cognitive load while fostering germane load (Evans et al., 2024; Sweller, 2023a, 2023b; Tarnag and Pei, 2023). Furthermore, it proactively addresses potential student difficulties and misconceptions documented in physics education research (Krijtenburg-Lewerissa et al., 2017; Majidy, 2024; Michelini and Stefanel, 2023) by carefully scaffolding concepts using a refined analogy-simulation approach. The sequence prioritizes deep conceptual understanding over

mathematical formalism and acknowledges the crucial affective and epistemic dimensions inherent in learning counter-intuitive science.

3.1 Participants and context

The intervention was implemented with a group of upper secondary students aged 16–18 years enrolled in the final 2 years of a general science track. The class consisted of 28 students (14 female, 14 male) who had previously completed introductory courses in classical mechanics and electromagnetism, as well as basic probability, but had not received formal instruction in quantum mechanics. The group was a whole-class cohort rather than a volunteer or elective group, ensuring that the intervention reached a typical cross-section of students within the school. The school is a private institution located in Ambato, Ecuador, operating under the national curriculum guidelines established by the Ministry of Education, which emphasize physics instruction primarily through classical topics with limited exposure to modern physics. Within this curriculum, the class can be considered representative of the broader target population, as students at this level generally share similar prior knowledge and curricular exposure. The intervention therefore reflects a realistic secondary school context where quantum concepts are not yet systematically integrated, but where students possess the foundational background necessary to engage with the proposed sequence.

3.2 Research design and data sources

The study was conducted as a classroom intervention within a design-based research (DBR) framework, which emphasizes iterative refinement of pedagogical approaches in authentic educational settings. This framework was chosen to align the theoretical principles of constructivism and cognitive load theory with practical classroom implementation, while simultaneously generating insights for both practice and research.

Multiple data sources were systematically collected throughout the intervention to capture different dimensions of student engagement and learning. These included:

- Written tasks completed by students during and after each phase of the sequence, used to assess evolving conceptual understanding.

- Classroom observations documented by the instructor and research team, focusing on student interactions, misconceptions, and use of representations.
- Video recordings of selected sessions, providing evidence of group discussions and teacher guidance.
- Semi-structured interviews with a subset of students conducted after the intervention, aimed at probing perceptions of analogy and simulation.
- Simulation logs generated by Qiskit activities, documenting students' exploration of quantum circuits and Bloch sphere visualizations.

Each source was collected at specific points in the sequence and served distinct analytical purposes. A summary is provided in [Table 1](#) to enhance transparency and support replication.

3.3 Analysis procedures

Student responses were analyzed using a coding scheme that categorized reasoning into three levels of conceptual understanding: (1) Classical reasoning, where entanglement was interpreted as pre-existing correlation or hidden variables; (2) Transitional reasoning, where students partially recognized quantum features but still relied on classical analogies; and (3) Quantum-consistent reasoning, where students articulated non-local correlations and superposition in line with accepted quantum descriptions. Each category was defined with clear criteria, and representative student excerpts were used to illustrate coding decisions. For example, a response such as “the magnets are already aligned before we separate them” was coded as Classical reasoning, while “the states remain linked even when separated, like in the simulation” was coded as Quantum-consistent reasoning.

Coding was conducted independently by two researchers with expertise in physics education. To ensure reliability, inter-rater agreement was calculated on a subset of 25% of the data, yielding a Cohen's kappa of 0.82, which indicates strong agreement. Discrepancies were discussed and resolved through consensus before final coding.

Quantitative data were also analyzed. Pre- and post-intervention written tasks were scored using a rubric aligned with the coding scheme, assigning numerical values to each level of reasoning

TABLE 1 Overview of data sources, timing, and analytical use.

Data source	Timing in sequence	Analogies/Simulations	Pedagogical function	Analytical purpose
Written tasks	End of each phase	Magnetic dipoles, Bloch sphere	Assess conceptual grasp of correlation and superposition	Assess conceptual understanding and misconceptions
Classroom observations	Continuous during all phases	All phases	Document engagement and mediation strategies	Document engagement, difficulties, and teacher mediation
Video recordings	Selected sessions (Phases 2–4)	Bloch sphere, Qiskit circuits	Capture group discourse around simulations	Analyze group discourse and instructional strategies
Student interviews	Post-intervention	Magnetic analogy vs. simulations	Probe perceptions of analogy limits and simulation value	Probe perceptions of analogy and simulation
Simulation logs	During computational phases (3–4)	Qiskit circuits	Track exploration of entanglement and superposition	Track exploration of circuits and visualization use

(Classical = 1, Transitional = 2, Quantum-consistent = 3). Scores were aggregated to calculate mean shifts in conceptual understanding. Simple descriptive statistics (means, standard deviations) were reported, and paired-sample t-tests were applied to examine whether observed changes were statistically significant. Frequency counts of reasoning types across phases were also tabulated to document shifts in student discourse. This systematic approach strengthens confidence in the validity of the conclusions drawn from the data.

3.4 Phase 1: Engagement, prior knowledge activation, and contextualization (approx. 45–60 min)

This initial phase aims to spark student curiosity about quantum phenomena and establish the relevance of quantum mechanics, while simultaneously activating relevant prior knowledge and eliciting existing preconceptions. The phase begins with a motivational stimulus, typically a carefully chosen discrepant event presented *via* demonstration or video (e.g., conceptually illustrating wave-particle duality or quantum tunneling) without immediate quantum explanation. This approach is designed to induce cognitive conflict and stimulate initial questioning (Aktulun et al., 2024; Kang and Kim, 2025; Kumar, 2024; Zuccarini and Malgieri, 2024). Follow-up discussions focus on probing student observations and encouraging them to articulate explanations based on their existing classical physics frameworks, often highlighting, through guided questioning, the limitations of those frameworks.

Subsequently, activities focus on eliciting and activating prior knowledge crucial for the sequence. Leveraging established elicitation techniques, including structured brainstorming and focused diagnostic questioning (Didiș, 2015; Emigh et al., 2020; Krijtenburg-Lewerissa et al., 2017; Majidy, 2024), the pre-instructional conceptual landscape held by students regarding quantum mechanics—encompassing extant ideas, intuitive frameworks, and potential alternative conceptions—is meticulously surfaced and documented, explicitly earmarked for subsequent revisiting and conceptual refinement during later stages of the instructional sequence. Subsequently, an interactive consolidation phase ensues, potentially incorporating brief illustrative demonstrations, structured peer discourse, or focused question-and-answer sessions, dedicated to reinforcing prerequisite classical concepts. Particular emphasis is placed upon elementary magnetism—foundational for the forthcoming analogical reasoning—and rudimentary probability, integral to apprehending the intrinsically probabilistic descriptive framework of QM, thereby establishing a requisite common conceptual foundation among learners. Finally, this phase contextualizes the learning journey. The upcoming analogy is framed explicitly, managing expectations about its scope: “To begin exploring. Entanglement, we’ll use familiar magnets as a helpful first step, but keep in mind, quantum mechanics holds surprises these everyday objects cannot fully capture.” Furthermore, brief mentions of real-world quantum applications (e.g., quantum computing, secure communication) are introduced to enhance student motivation and underscore the topic’s contemporary significance (Kaushik et al., 2023; Loviseti et al., 2024; Nautiyal et al., 2025).

3.5 Phase 2: A foundational analogy—exploring correlation (approx. 45–60 min)

This phase utilizes a tangible analogy—interacting magnetic dipoles—to introduce the foundational concept of correlation relevant to entanglement, begin distinguishing between local interactions and non-locality, and introduce the idea of measurement revealing a definite state. Necessary materials include pairs of marked magnets (e.g., bar or disc magnets), opaque containers, and student worksheets designed to guide the exploration, data recording, and subsequent reflection on the analogy’s correspondences and explicitly noted limitations. The pedagogical approach focuses on leveraging concrete experience to build an intuitive, albeit incomplete, bridge towards abstract quantum concepts (Cruz-Hastenreiter, 2015; Didiș, 2015; Nautiyal et al., 2025; Weissman et al., 2022).

The activities begin with guided exploration, where students work in small collaborative groups (Brundage et al., 2023; Rasjid and Bahar, 2023; Rodriguez et al., 2020; Rodriguez et al., 2025). They manipulate pairs of magnets within opaque containers, repeatedly observing and recording the resulting orientations after agitation. Students typically discover a consistent anti-parallel alignment (N-S or S-N) and calculate the frequencies of these outcomes, engaging them through active learning and data collection. Following this exploration, the core analogy is explicitly introduced: magnet orientation (North-up/South-up) is mapped to qubit computational basis states ($|1\rangle/|0\rangle$), and the observed perfect anti-correlation is directly linked to the concept of correlation between potentially entangled particles. The specific mappings and crucial limitations guiding this discussion are summarized in Table 2. Immediately, however, a crucial distinction is made to strategically introduce non-locality. Students are guided to recognize that the magnets’ correlation relies on local interactions (mediated by proximity and fields), which is explicitly contrasted with quantum entanglement’s signature non-local character: “This connection “at a distance,” violating classical constraints, is a key quantum mystery our magnets cannot replicate” (Brang et al., 2024; Batle et al., 2017; Faletič et al., 2025; Michelini and Stefanel, 2023). Furthermore, the analogy’s representation of superposition is addressed tentatively. The magnets’ unknown state before observation is framed as a weak parallel, but its critical limitation—representing classical uncertainty (lack of knowledge) rather than ontological quantum superposition (an inherent property)—is explicitly discussed, promising a more faithful visualization in the next phase (*via* the Bloch sphere). The act of observing the now-definite magnet orientation is then linked to the concept of measurement yielding a specific outcome, noting implicitly its deterministic nature in the analogy compared to the probabilistic nature in QM. Finally, having explored the tangible correlation and its crucial limitations, the term ‘quantum entanglement’ is formally introduced as the phenomenon being investigated.

3.6 Phase 3: Extending understanding—simulation and visualization (approx. 45–60 min)

Building upon the initial exploration *via* analogy, this phase aims to deepen understanding by introducing the Bloch sphere as a crucial tool for visualizing quantum superposition and using a Qiskit-based

TABLE 2 Pedagogical analysis of the magnetic dipole analogy for introducing quantum entanglement concepts.

Quantum concept	Magnetic analog	Correspondence	Key limitations	Pedagogical rationale/didactic implications
Qubit	0),	1)	North (N)/South (S) poles	Represents discrete, distinguishable binary states.
Superposition	Undefined orientation before observation	Represents an idea of a non-definite state before measurement. <i>Weak analogy.</i>	Classical uncertainty vs. quantum ontology: analog shows lack of knowledge; QM superposition is an inherent property (linear combination). Cannot represent phase. No interference effects.	Crucial contrast point: introduce the concept of non-definite states BUT immediately and explicitly contrast classical ignorance with quantum reality. Motivates need for richer models (Bloch sphere, simulation).
Measurement	Observing magnet's definite orientation (N or S)	Represents measurement yielding a specific, definite outcome ("collapse").	Classical revelation vs. quantum creation/probability: analog implies revealing pre-existing state deterministically; QM measurement is probabilistic and fundamentally alters the state. Analog measurement does not affect potential future measurements comparably.	Introduce measurement simply BUT use limitations later (Phase 4) to highlight the probabilistic nature and active role of measurement in QM, contrasting with classical observation.
Entanglement (correlation aspect only)	Anti-parallel alignment (N-S or S-N) due to interaction	Represents perfect (anti-) correlation between two systems.	Locality vs. non-locality: analog correlation arises from local magnetic field interactions; QM entanglement exhibits non-local correlations (violating Bell inequalities). Analog subject to macroscopic decoherence.	Introduce the core concept of perfect correlation tangibly. Crucially, immediately contrast the analog's locality with quantum non-locality ("spooky action") as a key conceptual leap and mystery, leveraging the limitation.
Spin	N/A (or overall magnet orientation)	No direct correspondence.	Intrinsic quantum property vs. macroscopic effect: spin is fundamental, intrinsic property without classical analog; magnetization is a collective, emergent classical phenomenon.	Explicitly state the lack of direct correspondence to prevent misconceptions (e.g., avoid conflating spin with classical rotation or the magnet's bulk property). Can briefly note magnetism originates from quantum spin, but is not equivalent.
Bloch sphere	N/A	N/A (analog is discrete binary)	Cannot represent continuous superposition states or relative phase graphically.	Highlights the need for more sophisticated visualization tools (like the Bloch sphere itself, introduced in Phase 3) to represent qubit states faithfully.

Summary of intended conceptual correspondences (for qubit states, correlation, measurement) and explicitly addressed limitations (regarding superposition, non-locality, and the classical nature of the analog) leveraged as contrast points within the proposed didactic sequence. This table summarizes key correspondences and limitations of the magnetic dipole analogy as employed in the proposed didactic sequence. Limitations are not merely acknowledged but are strategically leveraged as pedagogical contrast points during classroom discussions (esp. Phases 2 and 4) to highlight uniquely quantum features and motivate the introduction of more formal representations like the Bloch sphere and quantum simulations.

simulation to model entanglement creation and measurement. Key objectives include enabling students to connect the simulation back to the analogy while critically highlighting quantum concepts that transcend the analogy's limits, and offering opportunities for differentiated exploration. Necessary materials include student access to computers with internet connectivity (for web-based Qiskit access or local installation), a projector for demonstrations, and a structured worksheet or Jupyter notebook containing instructions, commented code snippets, guiding questions for analysis, and space for reflection (Angara et al., 2020; Cobo et al., 2022; Khatib, 2024). The phase commences with the introduction of the Bloch sphere, presented conceptually as a necessary geometric model to visually represent superposition states—a feature the discrete North/South magnet analogy could not adequately capture. The instructor explains the meaning of the poles ($|0\rangle$, $|1\rangle$) and the equator (equal superposition states) without delving into complex mathematical formalism (Hu et al., 2024; Levy and Singh, 2025; Pospiech et al., 2021; Theodoropoulou

et al., 2024). To better comprehension, it can be represented a concrete visual representation such as the Bloch sphere showing the state $|0\rangle$ at the north pole (see Figure 1).

The core activity is a guided quantum simulation using Qiskit to model the creation and measurement of a Bell state (entanglement). Recognizing the potential cognitive load associated with both the quantum concepts and the programming environment, a guided-interactive approach is employed. This utilizes a pre-prepared, well-commented Python script (The entire code, complete with comments, is included in the Supplementary Material) to ensure accessibility for secondary students and minimize extraneous load (Renken et al., 2016; Sweller, 2023a, 2023b; van Nooijen et al., 2024). Throughout this activity, constant reference to the analogy guides discussion; key Qiskit operations (like Hadamard for superposition, CNOT for entanglement, and measurement) are explicitly compared to the magnet exploration, identifying useful parallels while simultaneously reinforcing the crucial limitations and differences identified in Phase

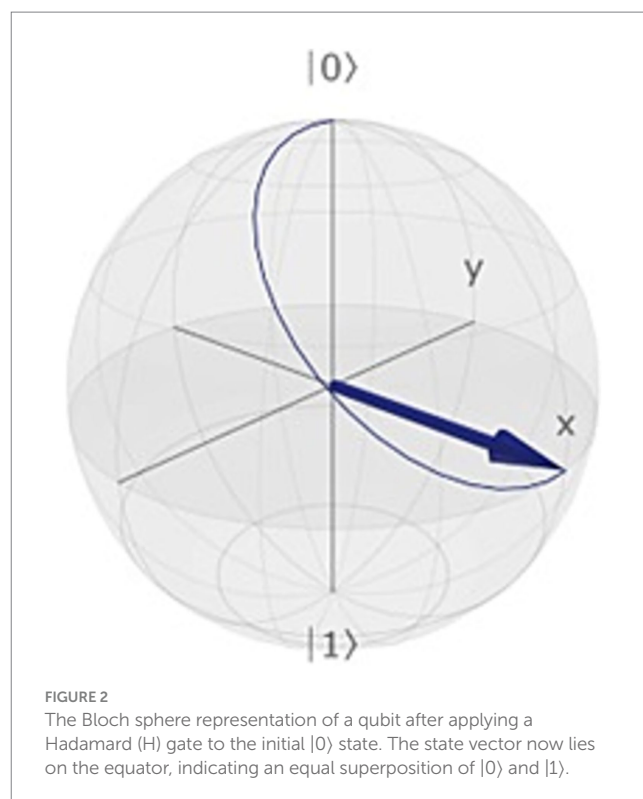
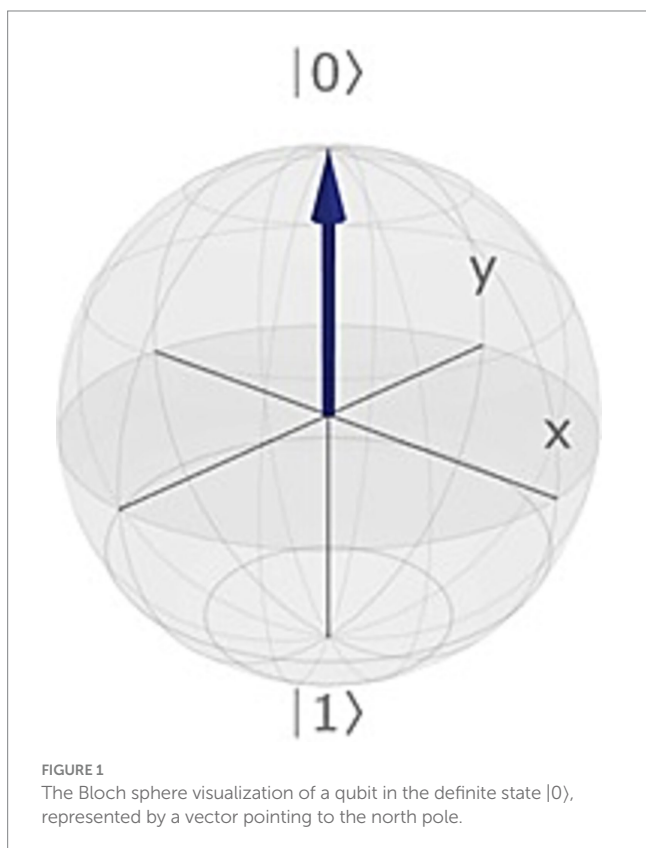
2 (e.g., non-locality, classical vs. quantum uncertainty). The Hadamard gate is crucial for creating superposition from a definite state; it shows the resulting state on the Bloch sphere after applying a Hadamard gate to a qubit initially in the $|0\rangle$ state (see Figure 2). Students are then encouraged to engage in collaborative analysis of the simulation outputs (result histograms, Bloch sphere visualizations of qubit states before measurement), so, a visualization of a quantum circuit, which uses fundamental gates to entangle two qubits is presented (see Figure 3). A Think-Pair-Share structure is recommended here to promote peer discussion, knowledge articulation, and active processing before a whole-class synthesis (Brundage et al., 2023; Kilpeläinen-Pettersson et al., 2025; Taihuttu et al., 2024). A key pedagogical step involves explicitly comparing the simulation and the analogy: students are guided to recognize how the simulation's histogram confirms the perfect correlation aspect observed with the magnets, while simultaneously appreciating how the Bloch sphere visualization provides a much more faithful representation of superposition—a concept the analogy failed to capture accurately. As an example, it is shown a histogram, where it reveals that the circuit represented in the Figure 3, only the correlated states $|00\rangle$ and $|11\rangle$ are measured when returning to the classical state, each with approximately 50% probability, mirroring the perfect anti-correlation seen in the analogy but arising from quantum entanglement (see Figure 4). This comparison serves as a natural point to contextualize decoherence conceptually, explaining it qualitatively as a primary reason why quantum superposition and entanglement are typically fragile and not observed in macroscopic systems like the magnets (Mulder, 2014; Bacciagaluppi, 2025).

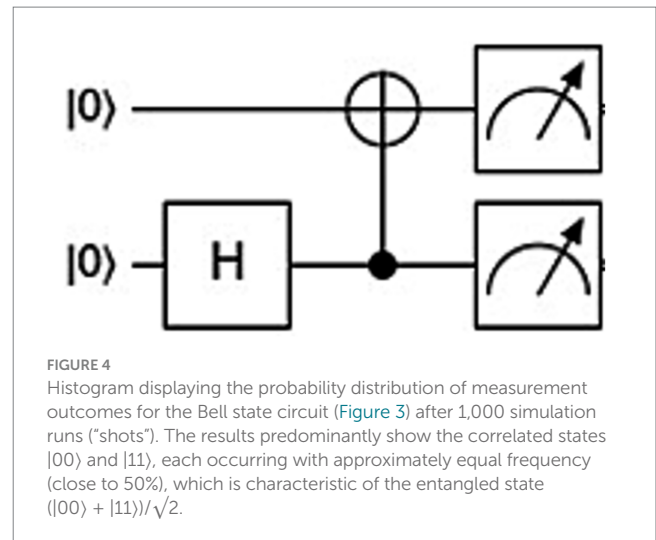
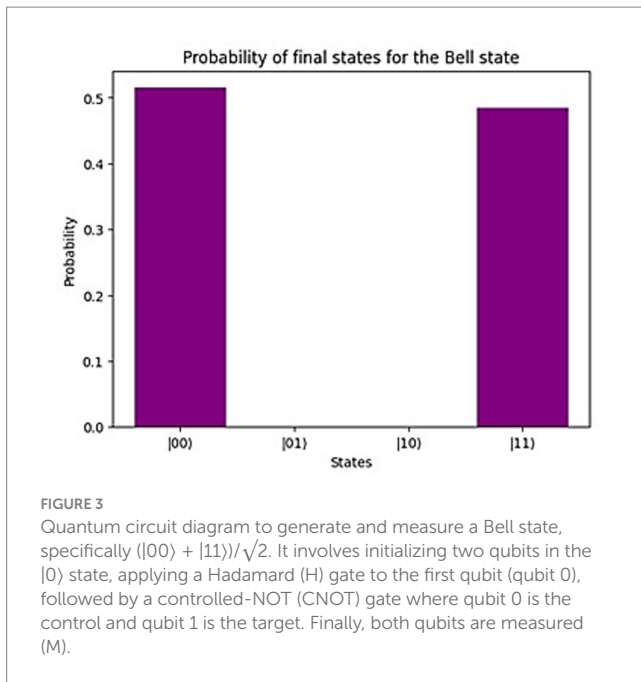
Finally, to cater to diverse student interests and paces, optional extensions are provided as challenge tasks for those ready for more

independent exploration (Jarnawi et al., 2025; Maeng and Bell, 2015; Montagnani et al., 2023; Winarto et al., 2024). Examples include modifying the provided script to generate a different Bell state (e.g., $(|01\rangle + |10\rangle)/\sqrt{2}$), investigating the effects of measurement in a different computational basis (e.g., the X-basis), or exploring the impact of applying other single-qubit gates (like X or Z gates). These extensions allow for deeper engagement and foster student agency without disrupting the core learning trajectory for the entire class (Angara et al., 2022; Bouchée et al., 2021a,b; Nautiyal et al., 2025; Rodriguez et al., 2020; Sun et al., 2024; Tarnj and Pei, 2023).

3.7 Phase 4: Synthesis, reflection, and deeper inquiry (approx. 45–60 min)

This crucial synthesis phase aims to consolidate student understanding by explicitly comparing the pedagogical tools used (analogy and simulation), deepen conceptual grasp of challenging topics like non-locality, address persistent questions, foster metacognitive reflection, and firmly connect learned concepts to real-world applications. The phase employs several activities designed to facilitate these higher-order processes. It begins with a structured comparative discussion focused on evaluating the analogy and simulation. To ensure diverse perspectives are considered, students initially engage in structured small group discussions, potentially using assigned roles (e.g., “Analogy Proponent,” “Simulation Advocate,” “Key Difference Analyst”), before a whole-class synthesis (Blings and Maxey, 2016; Krijtenburg-Lewerissa et al., 2017; Nautiyal et al., 2025; Prahani et al., 2021; Serbin and Wawro, 2024). This discussion explicitly guides students to recall and articulate the specific limitations of the magnetic analogy identified in previous phases (e.g., its classical nature, locality, inadequate





superposition representation, as detailed in Table 2) and contrast them with the capabilities and representations of the quantum simulation, ultimately addressing questions like, "What was the pedagogical value of the magnet analogy, even considering its limitations?"

Following the comparison of tools, the sequence incorporates a guided thought experiment to promote deeper inquiry into non-locality (Borish and Lewandowski, 2024; Cui, 2025; Velentzas et al., 2007). Students are prompted to contrast the classical scenario ("Imagine setting up the magnets locally and separating them – the correlation is due to that initial local setup") with the quantum case ("Now, consider entangled qubits. Experiments related to Bell's theorem, which fundamentally limits classical explanations based on pre-existing local properties, show correlations that cannot be explained by any local pre-programming like the magnets. How does this "spooky action" differ fundamentally?"). This activity intentionally pushes students beyond understanding simple correlation towards grappling with the profoundly counter-intuitive nature of quantum connections.

Recognizing that learning counter-intuitive science involves more than just cognitive processing, this phase also explicitly addresses affective and epistemic responses. The instructor openly acknowledges during discussions that quantum concepts can feel confusing or "weird," validating student experiences of wonder or frustration as normal aspects of engaging with frontier science. Creating a safe classroom climate for these reactions is emphasized as important for sustained engagement (Otero and Fanaro, 2019; Patterson and Ding, 2025; Taşar and Heron, 2023; Yonai and Blonder, 2025; Zohar and Levy, 2021). Subsequently, the relevance loop is closed by revisiting the real-world applications mentioned in Phase 1. Students are asked to connect their enhanced understanding of superposition and entanglement to the potential of quantum technologies: "Based on what we have explored. How might these specific quantum properties enable powerful computing or secure communication in ways classical physics cannot?"

Finally, the phase concludes with individual written reflection. Students respond privately to carefully crafted prompts designed to encourage consolidation of understanding (e.g., explaining

entanglement in their own words, comparing the utility of the analogy and simulation for their learning) and foster metacognition (e.g., identifying remaining questions or points of confusion) (Bogdanović et al., 2022; Kaw et al., 2024; Dökme and Koyunlu Ünlü, 2021; Nautiyal et al., 2025; Patterson and Ding, 2025).

3.8 Computational simulation and educational role

The computational component of the sequence was implemented using Qiskit-based activities and Bloch sphere visualizations. Students interacted with a simulation environment where they could manipulate quantum circuits by selecting gates, running entanglement protocols, and observing the resulting state vectors. The interface displayed both numerical outputs (probability distributions) and graphical representations (Bloch spheres and correlation plots), allowing students to connect abstract quantum states with visual cues.

Entangled states were represented through correlated measurement outcomes across qubits. For example, when students applied a Hadamard gate followed by a CNOT, the simulation displayed the entangled state $|\Phi^+\rangle$, and subsequent measurements revealed non-classical correlations. Classroom activities emphasized interpreting these outputs: students compared the simulation results with their predictions based on the tangible analogy, discussing how correlations persisted even when qubits were separated in the model.

Several productive uses of the simulation were observed. Students often manipulated gates iteratively to test "what if" scenarios, which fostered exploration and hypothesis testing. They also used the Bloch sphere to visualize how entanglement differs from simple rotations or local operations. At the same time, common difficulties emerged. Some students initially misread the Bloch sphere, interpreting it as a physical trajectory rather than a state representation. Others confused probability distributions with deterministic outcomes. These difficulties were addressed through guided discussion, highlighting the contrast between classical expectations and quantum behavior.

Representative examples illustrate these dynamics. One student remarked, "I thought the qubits would behave independently, but the simulation shows they are always linked," which was coded as a shift toward quantum-consistent reasoning. Another student

misinterpreted the Bloch sphere as showing “the path of the particle,” prompting a class-wide clarification that the sphere represents state orientation rather than motion. These episodes demonstrate how the simulation served both as a tool for conceptual reinforcement and as a catalyst for recognizing the limits of classical intuition.

3.9 Phase 5: Integrated formative assessment

Underpinning the entire didactic sequence is a commitment to integrated formative assessment, functioning not as a separate phase but as a continuous process woven throughout all activities. Its primary objective is to continuously monitor students’ evolving conceptual understanding and learning processes, providing timely insights to dynamically inform and adapt instruction, rather than assigning summative grades (Lichtenberger et al., 2025; Nautiyal et al., 2025; Worku et al., 2025). This ongoing assessment utilizes a blend of strategies to capture diverse facets of student learning. Strategic questioning plays a fundamental role, employing varied prompts designed to probe different cognitive levels, from recall to analysis and evaluation, thereby revealing students’ thinking processes (Bano et al., 2025; Ghafar and Hazaymeh, 2024; Hill, 2016). Complementing this is careful observation of classroom dynamics, monitoring student interactions during collaborative tasks, their engagement with the analogy and simulations, and their contributions to discussions (Faletič, 2025; Kraus, 2024; Montagnani et al., 2023). Further insight is gained through the analysis of student reflections generated in Phase 4, reviewing their written work to gauge conceptual grasp, identify persistent questions, and assess their ability to articulate complex ideas (Kaw et al., 2024; Dökme and Koyunlu Ünlü, 2021). Optionally, brief, low-stakes conceptual quizzes can be employed as quick checks for understanding on key points.

Crucially, recognizing the challenge of teaching profoundly counter-intuitive topics like quantum entanglement, the formative assessment strategy extends beyond purely cognitive aspects to include deliberate attention to affective and epistemic dimensions. This involves being sensitive to students’ reactions—such as expressions of confidence, curiosity, or confusion—and potentially engaging with their developing epistemic beliefs about the nature of scientific models, the role of analogy, and the inherent “weirdness” of quantum theory itself (Patterson and Ding, 2025; Otero and Fanaro, 2019). Observing how students grapple with challenging concepts can be as informative for pedagogical adjustments as assessing their explicit conceptual statements. Ultimately, all information gathered through these diverse strategies feeds into an essential feedback loop, enabling the instructor to dynamically adjust the pace, emphasis, or specific scaffolding techniques to better meet the evolving needs of the learners as they navigate this complex conceptual terrain (Damaševičius, 2025; Majidy, 2024; Ole and Gallos, 2023; Pollock et al., 2023).

This enhanced didactic sequence integrates collaborative strategies, opportunities for differentiation, deeper conceptual probes for non-locality, explicit connection to real-world relevance, and attention to affective/epistemic factors, aiming for a more holistic and potentially more impactful learning experience.

4 Results

The results are organized into subsections aligned with the research questions. Each subsection presents one or two central findings, supported by selected evidence from classroom dialogue, student work, and observations.

Students’ emerging conceptions of entanglement:

- Claim: students initially relied on classical reasoning (e.g., “the magnets are already aligned before separation”).
- Claim: several shifted toward quantum-consistent reasoning after engaging with the analogy and simulation (e.g., “the states remain linked even when separated, like in the simulation”).

Use of the tangible analogy:

- Claim: the magnetic dipole analogy provided a productive entry point for visualizing correlation.
- Claim: guided discussions helped students recognize its limits, prompting transition toward abstract reasoning.

Interaction with the simulation:

- Claim: the simulation enabled exploration of entangled states through gate manipulation and Bloch sphere visualization.
- Claim: difficulties emerged (e.g., misreading Bloch sphere as trajectory), but teacher mediation clarified these points, reinforcing learning.

5 Discussion

This article has addressed the pedagogical challenge of introducing quantum entanglement—an inherently abstract and counterintuitive concept for secondary school students (Brang et al., 2024; Batle et al., 2017; Faletič et al., 2025)—by seeking to overcome the recognized limitations of approaches overly reliant on mathematical formalism (Pospiech et al., 2021; Serbin and Wawro, 2024). To this end, a five-phase didactic sequence was proposed that strategically integrates a concrete, manipulable analogy (interacting magnets) with computational representations such as the Bloch sphere and Qiskit simulations. This concluding section discusses the pedagogical potential of this integrated proposal, its grounding in the relevant literature, limitations that must be considered, and its implications for both teaching practice and future research in quantum physics education.

5.1 Pedagogical potential of the proposal

It is argued that the synergistic integration of the tangible analogy with computational simulation, explicitly guided by constructivist and cognitive load principles, offers significant pedagogical potential for addressing the notorious complexity of quantum entanglement. The magnetic analogy acts as a crucial initial scaffold, providing an intuitive and accessible starting point that allows students to directly experience a system with observable correlations. This concrete anchor facilitates the introduction of the abstract concept of correlated states, mitigating the initial barrier of abstraction (Cruz-Hastenreiter, 2015; Didiş, 2015). However, acknowledging the

inherent risks of classical analogies, the sequence strategically transitions to computational representations. The Bloch sphere and Qiskit simulations are introduced not only to overcome specific limitations of the analogy—such as faithfully visualizing superposition or dynamically modeling entanglement creation—but also to function as a conceptual bridge towards more formal quantum descriptions (Weber and Wilhelm, 2020; Ahmed et al., 2021; Hu et al., 2024). This multiple representations approach (concrete-visual-symbolic), carefully sequenced and scaffolded as detailed in Section 3, is designed to actively manage cognitive load. It seeks to reduce intrinsic load through the initial analogy and conceptual segmentation, minimize extraneous load *via* clear visualizations and explicit guidance, and, crucially, foster germane load through reflective comparison between models and engagement with conceptual tasks (Sweller, 2023a, 2023b; Renken et al., 2016; van Nooijen et al., 2024). Complementarily, the sequence promotes active and constructivist learning through hands-on exploration, collaborative analysis, and guided discussion, enabling students to negotiate meaning and actively construct their understanding of these counter-intuitive concepts (Al-Kamzari and Alias, 2025; Nautiyal et al., 2025; Steffe and Ulrich, 2020). Finally, the combination of concrete manipulation, interaction with simulations, and connection to relevant applications is expected to enhance intrinsic motivation and engagement (Kaushik et al., 2023; Nautiyal et al., 2025; Evans et al., 2024). Altogether, it is postulated that this integrated, multi-faceted approach can facilitate a deeper, more robust, and meaningful conceptual understanding of entanglement, surpassing the limitations of more linear methods or those relying solely on formalism or simplistic analogies without critical analysis of their boundaries, particularly when facing the unique challenges of quantum complexity.

5.2 Connection to the literature

The robustness of the presented pedagogical proposal lies in its explicit synthesis of findings from several key areas of educational research. The sequence design is not based on a single pillar but rather integrates insights from the extensive literature on persistent learning difficulties in quantum mechanics, seeking to proactively address common misinterpretations of superposition, entanglement, and measurement (Majidy, 2024; Krijtenburg-Lewerissa et al., 2017; Michelini and Stefanel, 2023). Concurrently, the approach taken to the use of analogies draws directly from research on their effective implementation, incorporating principles from frameworks like TWA and the critical need to explicitly manage limitations to prevent alternative conceptions (Cruz-Hastenreiter, 2015; Didiş, 2015; Mammino, 2023; Rodriguez et al., 2025). Similarly, the incorporation of computational visualizations and simulations is justified by accumulated evidence regarding their value in representing abstract phenomena, facilitating active exploration, and potentially mitigating cognitive load in complex domains like physics (Weber and Wilhelm, 2020; Ahmed et al., 2021; Tarnag and Pei, 2023; Angara et al., 2022). Fundamentally, the overall architecture of the sequence is imbued with principles from robust learning theories—constructivism, emphasizing the learner's active construction of meaning (Al-Kamzari and Alias, 2025; Nautiyal et al., 2025; Weissman et al.,

2022), and Cognitive Load Theory, guiding strategies to manage the inherent complexity of the subject matter and optimize information processing (Sweller, 2023a, 2023b; Evans et al., 2024). It is this convergence of principles and evidence that provides the proposal with its rationale and pedagogical potential.

5.3 Limitations of the proposal

It is essential to transparently acknowledge the inherent limitations of this proposal to contextualize its scope and guide future improvements. Firstly, although the sequence pedagogically utilizes the limitations of the magnetic analogy as contrast points (Phases 2 and 4), its classical nature and reliance on local interactions prevent a faithful representation of key quantum aspects such as ontological superposition or non-locality (evidenced by Bell inequality violations). While the strategy of using these discrepancies is theoretically sound (Didiş, 2015; Mammino, 2023), its practical success requires very careful didactic implementation by the instructor, who must actively guide students to ensure understanding of the fundamental difference and avoid inadvertently reinforcing classical intuitions. Secondly, the Qiskit simulation, while a more powerful tool, necessarily constitutes a simplified abstraction. This simplification, pedagogically justified to manage cognitive load and focus on core concepts at the secondary level, omits the physical complexities of qubit implementation, detailed environmental interactions, and the nuances of decoherence (Mulder, 2014; Bacciagaluppi, 2025). Finally, the most significant limitation of this work in its current phase is the lack of rigorous empirical validation. The sequence presented here is a proposal grounded in theory and prior research, but its actual effectiveness and impact on student understanding and attitudes must be systematically investigated, as detailed in the directions for future research (Section 5.5).

5.4 Pedagogical implications and recommendations

Beyond its inherent limitations, the design and analysis of this integrated analogy-simulation proposal, grounded in learning theories, yield several pedagogical implications potentially transferable to the teaching of quantum physics and other complex, counter-intuitive scientific domains. Firstly, the sequence underscores the importance of viewing analogies not as final explanations but as initial scaffolding tools and, crucially, as points of contrast. This requires didactic design and management that explicitly addresses and pedagogically leverages their limitations to build deeper understanding (as exemplified in Phases 2 and 4). Secondly, it reinforces the critical value of visualization and simulation tools (used in Phase 3) as indispensable bridges to abstract concepts, highlighting that their effectiveness is enhanced when coherently integrated with other representations and appropriately guided (cf. Ahmed et al., 2021; Tarnag and Pei, 2023). Thirdly, the proposal as a whole exemplifies the need for adopting student-centered, constructivist approaches, reflected in the exploration, collaborative discussion, and reflection activities (Phases 2–4), while also recognizing the importance of explicitly addressing the affective and

epistemic dimensions (addressed in Phase 4) that inevitably arise when confronting ideas challenging intuition (Otero and Fanaro, 2019; Patterson and Ding, 2025). Finally, the integral design of continuous formative assessment (Phase 5) highlights its indispensable role in monitoring and adapting instruction to the complex evolution of student understanding in these topics (cf. Lichtenberger et al., 2025; Ole and Gallos, 2023). The synergy between these components—managed analogy, guided simulation, active construction, holistic attention, and continuous adaptation—emerges as a key principle.

Derived from this design, practical recommendations are offered for educators. It is essential to dedicate explicit and sufficient time to the comparative discussion of the limitations of any analogy employed (following the model of Phase 4), as the greatest potential for quantum conceptual learning often lies in the contrast. It is also recommended to actively employ and connect multiple representations (concrete, visual, symbolic-conceptual, as modeled across Phases 2–4) to facilitate understanding from different perspectives. Furthermore, fostering a safe classroom climate (as intended in Phase 4) that validates inquiry, debate, and the expression of difficulty or wonder is crucial, recognizing these as part of the learning process. Lastly, maintaining instructional flexibility is advised, using insights from continuous formative assessment (Phase 5) to adapt pacing and activities to the actual and diverse needs of the students. These recommendations, though derived from this specific context, may inform the teaching of other abstract scientific topics.

5.5 Future research

This work opens diverse and necessary avenues for future research to validate and refine the pedagogical proposal delineated herein. The undisputed priority lies in the systematic empirical evaluation of the sequence's effectiveness. This requires rigorous studies, ideally quasi-experimental, comparing the conceptual, attitudinal, and epistemic learning outcomes of students using this sequence against those in control groups employing traditional or alternative approaches. Concurrently, detailed qualitative studies (through classroom observations, analysis of student artifacts, interviews) are crucial to gain deep insights into students' reasoning processes as they interact with the analogy-simulation integration: specifically, how they negotiate the analogy's limitations (addressed in Phases 2 and 4), how they construct meaning from comparing representations (central to Phases 3 and 4), and how their collaborative discussions unfold. Subsequent research could explore the effect of implementation variations, such as comparing the magnetic analogy with other initial analogies or designing and evaluating more sophisticated computational simulations (e.g., modeling different types of entangled states or gradually introducing decoherence effects). Given the sequence's complexity and reliance on instructor guidance, investigating teacher professional development needs and perspectives during implementation would also be essential. Furthermore, the development and validation of assessment instruments specifically aligned with the deep conceptual understanding goals (particularly regarding non-locality) targeted by this sequence, going beyond traditional

measures, would be valuable. Finally, longitudinal studies would allow exploration of learning retention and the long-term impact of this approach on students' sustained interest in quantum physics and STEM pathways.

6 Conclusion

The growing influence of quantum technologies in the 21st century demands a level of quantum literacy that transcends university settings and extends into secondary education. This article addressed the pedagogical challenge of introducing quantum entanglement, a central and paradigmatic phenomenon of quantum mechanics, to students typically lacking advanced mathematical training. A five-phase didactic sequence was presented that strategically integrates a concrete analogy (interacting magnets) with computational representations (Bloch sphere, Qiskit simulation), seeking to overcome the limitations of traditional approaches and promote active, constructivist, and cognitively efficient learning.

While we acknowledge that the present proposal, being theoretical in nature, still lacks direct empirical validation—its primary limitation—we maintain that its contribution lies in several key aspects. It provides a solid grounding synthesizing research on QM learning difficulties, the pedagogical use of analogies and simulations, and relevant learning theories. It offers a detailed and coherent didactic design that serves as a practical guide, including referenced supporting materials. And, crucially, it performs an explicit analysis of the analogy's limitations, proposing a strategy to pedagogically leverage them as contrast points, a vital aspect for preventing misconceptions when teaching counter-intuitive topics.

We believe that this integrated approach, by reflectively connecting tangible experience with visual and symbolic-computational representations while managing cognitive load, offers a promising pathway for secondary students to begin constructing meaningful conceptual understanding of quantum entanglement. We consider this effort a necessary step in preparing informed citizens and future innovators for an era increasingly influenced by quantum science.

This work, therefore, is offered as a catalyst and an invitation for future research in this critical area. We urge the science and physics education community to prioritize the empirical evaluation of this and similar pedagogical proposals in real classroom contexts, employing rigorous designs and attending not only to conceptual understanding but also to long-term effects on attitudes and epistemology. It is equally important to systematically explore the optimal combination of different representations (analogies, visualizations, simulations) for various quantum concepts and educational levels. There is also an urgent need to continue the development and study of technological tools that facilitate active exploration and meaning-making, as well as to deepen research into the specific cognitive and affective processes involved in learning QM. Finally, these efforts must inform the design of secondary school QM curricula that are conceptually rigorous, pedagogically innovative, and genuinely accessible.

We consider sustained investment in didactic research and development in quantum physics crucial for building a scientifically literate society capable of navigating and participating in the

unprecedented challenges and opportunities presented by the emerging quantum era.

Data availability statement

The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding authors.

Author contributions

DC-S: Conceptualization, Investigation, Writing – review & editing. ST: Methodology, Supervision, Writing – original draft. WL: Data curation, Formal analysis, Writing – review & editing. HO: Data curation, Formal analysis, Writing – original draft.

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Conflict of interest

ST was employed by HessQ Inc.

The remaining authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

References

- Ahmed, S. Z., Jensen, J. H. M., Weidner, C. A., Sørensen, J. J., Mudrich, M., and Sherson, J. F. (2021). Quantum composer: a programmable quantum visualization and simulation tool for education and research. *Am. J. Phys.* 89, 307–316. doi: 10.1119/10.0003396
- Aktulun, Ö. U., Kaya, Ü. Ü., Gözümlü, A. İ. C., Kalogiannakis, M., and Papadakis, S. (2024). Igniting curiosity: the role of STEAM education in enhancing early academic, language skills and motivation for science. *Int. J. Mod. Educ. Comput. Sci.* 16, 1–20. doi: 10.5815/ijmecs.2024.05.01
- Al-Kamzari, F., and Alias, N. (2025). A systematic literature review of project-based learning in secondary school physics: theoretical foundations, design principles, and implementation strategies. *Humanit. Soc. Sci. Commun.* 12:286. doi: 10.1057/s41599-025-04579-4
- Angara, P. P., Stege, U., and MacLean, A. (2020) Quantum computing for high-school students: an experience report. In. *2020 IEEE International Conference on Quantum Computing and Engineering (QCE)*. 323–329. Piscataway, NJ: IEEE
- Angara, P. P., Stege, U., MacLean, A., Müller, H. A., and Markham, T. (2022). Teaching quantum computing to high-school-aged youth: a hands-on approach. *IEEE Trans. Quantum Eng.* 3:4501511. doi: 10.1109/TQE.2022.3178102
- Bacciagaluppi, G. (2025). “The role of decoherence in quantum mechanics” in The Stanford encyclopedia of philosophy. ed. E. N. Zalta (Stanford, CA: Metaphysics research lab, Stanford University).
- Bano, S., Sharar, T., and Khalil, A. (2025). Cultivating critical thinking skill in students through questioning technique: an action research study. *J. Asian Dev. Stud.* 14, 1225–1236. doi: 10.62345/jads.2025.14.1.98
- Bao, L., Koenig, K., Xiao, Y., Fritchman, J., Zhou, S., and Chen, C. (2022). Theoretical model and quantitative assessment of scientific thinking and reasoning. *Phys. Rev. Phys. Educ. Res.* 18:010115. doi: 10.1103/PhysRevPhysEducRes.18.010115
- Barr, A. J., Fabbrichesi, M., Floreanini, R., Gabrielli, E., and Marzola, L. (2024). Quantum entanglement and Bell inequality violation at colliders. *Prog. Part. Nucl. Phys.* 139:104134. doi: 10.1016/j.pnpnp.2024.104134
- Batle, J., Abutalib, M., and Abdalla, S. (2017). Anomaly of non-locality and entanglement in teaching quantum information. *Rev. Mexicana Física* 63, 1–5. doi: 10.31349/RevMexFisE.63.1
- Bitzenbauer, P. (2021). Quantum physics education research over the last two decades: a bibliometric analysis. *Educ. Sci.* 11:699. doi: 10.3390/educsci11110699
- Blings, S., and Maxey, S. (2016). Teaching students to engage with evidence: an evaluation of structured writing and classroom discussion strategies. *J. Polit. Sci. Educ.* 13, 15–32. doi: 10.1080/15512169.2016.1168303
- Bøe, M. V., Henriksen, E. K., and Angell, C. (2018). Actual versus implied physics students: how students from traditional physics classrooms related to an innovative approach to quantum physics. *Sci. Educ.* 102, 649–667. doi: 10.1002/sc.21339
- Bogdanović, I. Z., Stanisavljević, J. D., Rodić, D. D., Rončević, T. N., and Zouhor, Z. A. M. (2022). The impact of using the modified know-want-learn strategy in physics teaching on students’ metacognition. *South Afr. J. Educ.* 42:2096. doi: 10.15700/saje.v42n4a2096
- Borish, V., and Lewandowski, H. J. (2024). Student reasoning about quantum mechanics while working with physical experiments. *Phys. Rev. Phys. Educ. Res.* 20:020135. doi: 10.1103/PhysRevPhysEducRes.20.020135
- Bouchée, T., de Putter-Smits, L., Thurlings, M., and Pepin, B. (2021b). Towards a better understanding of conceptual difficulties in introductory quantum physics courses. *Stud. Sci. Educ.* 58, 183–202. doi: 10.1080/03057267.2021.1963579
- Bouchée, T., Thurlings, M., de Putter-Smits, L., and Pepin, B. (2021a). Investigating teachers’ and students’ experiences of quantum physics lessons: opportunities and challenges. *Res. Sci. Technol. Educ.* 41, 777–799. doi: 10.1080/02635143.2021.1948826
- Brang, M., Franke, H., Greinert, F., Ubben, M. S., Hennig, F., and Bitzenbauer, P. (2024). Spooky action at a distance? a two-phase study into learners’ views of quantum entanglement. *EPL Quantum Technol.* 11:33. doi: 10.1140/epjqt/s40507-024-00244-y
- Brundage, M. J., Malespina, A., and Singh, C. (2023). Peer interaction facilitates co-construction of knowledge in quantum mechanics. *Phys. Rev. Phys. Educ. Res.* 19:020133. doi: 10.1103/PhysRevPhysEducRes.19.020133
- Brundage, M. J., Meltzer, D. E., and Singh, C. (2025). Investigating the impact of problem properties on introductory and advanced student responses to introductory thermodynamics conceptual problems. *Phys. Rev. Phys. Educ. Res.* 21:010127. doi: 10.1103/PhysRevPhysEducRes.21.010127

Correction note

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- Chiarelli, P., and Chiarelli, S. (2024). The computational universe: quantum quirks and everyday reality, actual time, free will, the classical limit problem in quantum loop gravity and causal dynamical triangulation. *Quantum Rep.* 6, 278–322. doi: 10.3390/quantum6020020
- Cobo, A., Rocha, R., Collantes, M., Espinola, J. E., and Mora, E. (2022). Implementation of virtual laboratories with Jupyter notebooks: practical experiences in computer science and mathematics. In *EDULEARN22 Proceedings* 8746–8753. IATED
- Cruz-Hastenreiter, R. (2015). Analogies in high school classes on quantum physics. *Procedia. Soc. Behav. Sci.* 167, 38–43. doi: 10.1016/j.sbspro.2014.12.639
- Cui, Q. (2025). A thought experiment suggests a simple interpretation of quantum entanglement. *J. Mod. Phys.* 16, 219–228. doi: 10.4236/jmp.2025.162014
- Damaševičius, R. (2025). “Quantum pedagogy: a 21st century framework for education 5.0” in Impacts of AI on students and teachers in education 5.0. ed. F. D. Mobo (Mumbai: IGI Global), 386–429.
- De Ambrosis, A., and Levirini, O. (2010). How physics teachers approach innovation: an empirical study for reconstructing the appropriation path in the case of special relativity. *Phys. Rev. ST. Phys. Educ. Res.* 6:020107. doi: 10.1103/PhysRevSTPER.6.020107
- De Ronde, C. (2023a). “Measuring quantum super positions” in Non-reflexive logics, non-individuals, and the philosophy of quantum mechanics. eds. J. R. B. Arenhart and R. W. Arroyo (Berlin: Springer), 259–273.
- De Ronde, C. (2023b). The (quantum) measurement problem in classical mechanics editors. D. Aerts, Sassoli Bianchi M. de and S. Sozzo Probing the meaning of quantum mechanics Singapore: World Scientific Publishing
- Didiș, N. (2015). The analysis of analogy use in the teaching of introductory quantum theory. *Chem. Educ. Res. Pract.* 16, 355–376. doi: 10.1039/C5RP00011D
- Dökme, İ., and Koyunlu Ünlü, Z. (2021). The challenge of quantum physics problems with self-metacognitive questioning. *Res. Sci. Educ.* 51, 783–800. doi: 10.1007/s11165-019-9821-4
- Doyle, T. (2023). “The drive for impact: science education in the quantum age” in Challenges in science education. eds. G. P. Thomas and H. J. Boon (London UK: Palgrave Macmillan).
- Emigh, P. J., Gire, E., Manogeu, C. A., Passante, G., and Shaffer, P. S. (2020). Research-based quantum instruction: paradigms and tutorials. *Phys. Rev. Phys. Educ. Res.* 16:020156. doi: 10.1103/PhysRevPhysEducRes.16.020156
- Evans, P., Vansteenkiste, M., Parker, P. D., and Lonsdale, C. (2024). Cognitive load theory and its relationships with motivation: a self-determination theory perspective. *Educ. Psychol. Rev.* 36:7. doi: 10.1007/s10648-023-09841-2
- Faletić, S. (2025). How analogies helped novice students think about superposition states and collapse in quantum mechanics. *EPJ Quantum Technol.* 12. doi: 10.1140/epjqt/s40507-025-00309-6
- Faletić, S., Michelini, M., and Pospiech, G. (2025). Teaching and learning quantum entanglement: a discussion on different perspectives. *J. Phys. Conf. Ser.* 2950:e012025. doi: 10.1088/1742-6596/2950/1/012025
- Ghafar, Z. N., and Hazaymeh, O. (2024). The effective questioning in the classroom: an overview of the techniques used by instructors. *Int. J. Child. Educ.* 5, 1–14. doi: 10.33422/ijce.v5i2.676
- Gkintoni, E., Antonopoulou, H., Sortwell, A., and Halkiopoulou, C. (2025). Challenging cognitive load theory: the role of educational neuroscience and artificial intelligence in redefining learning efficacy. *Brain Sci.* 15:203. doi: 10.3390/brainsci15020203
- Grossi, M., Di Meglio, A., and Vallecorsa, S. (2024). “Spooky quantum action: from thought experiments to real world quantum technology application” in New frontiers in science in the era of AI. eds. M. Streit-Bianchi and V. Gorini (Berlin: Springer).
- Hennig, F., Tóth, K., Veith, J., and Bitzenbauer, P. (2024). Mathematical sense making of quantum phenomena using Dirac notation: its effect on secondary school students’ functional thinking about photons. *EPJ Quantum Technol.* 11:61. doi: 10.1140/epjqt/s40507-024-00274-6
- Hill, J. B. (2016). Questioning techniques: a study of instructional practice. *Peabody J. Educ.* 91, 660–671. doi: 10.1080/0161956X.2016.1227190
- Hobson, A. (2024). “Quantum confusion: foundations are in risky disarray” in Fields and their quanta (Berlin: Springer), 1–19.
- Hossain, K. A. (2023). The potential and challenges of quantum technology in modern era. *J. Sci. Res.* 11:41. doi: 10.31364/SCIRJ/v11.i6.2023.P0623953
- How, M.-L., and Cheah, S.-M. (2024). Forging the future: strategic approaches to quantum AI integration for industry transformation. *AI* 5, 290–323. doi: 10.3390/ai5010015
- Hu, P., Li, Y., Mong, R. S. K., and Singh, C. (2024). Student understanding of the Bloch sphere. *Eur. J. Phys.* 45:025705. doi: 10.1088/1361-6404/ad2393
- Huseby, A., and Bungum, B. (2019). Observation in quantum physics: challenges for upper secondary physics students in discussing electrons as waves. *Phys. Educ.* 54:e065002. doi: 10.1088/1361-6552/ab3694
- Irvani, A. I., Rochintaniawati, D., Riandi, R., Sinaga, P., and Henukh, A. (2024). Analysis of quantum physics lectures from the perspective of the MBKM and OBE based higher education curriculum. *Jurnal Pendidikan Fisika dan Teknologi* 10, 44–54. doi: 10.29303/jpft.v10i1.6390
- Jaeger, G. (2014). “Quantum theory and locality” in Quantum Objects: non-local correlation, causality and objective indefiniteness in the quantum world (Berlin: Springer).
- Jarnawi, M., Haeruddin, H., Werdhiana, I. K., Syamsuriwal, S., and Mu’aziyah, S. E. S. (2025). Integrating thinking styles into differentiated instruction: enhancing learning outcomes in science education. *Integr. Sci. Educ. J.* 6, 47–53. doi: 10.37251/isej.v6i1.1328
- Kang, J., and Kim, J. (2025). Why do people not desire to know all their unknowns? exploring the potential of interest as a factor in arousing curiosity in science. *Instr. Sci.* 53, 527–566. doi: 10.1007/s11251-024-09695-3
- Kaushik, P., Vu, N., Yeung, C., Sorak, N., Khazaei, P., and Azevedo Cabral, D. G. (2023). Impact of quantum mechanics-based workshops on developing high school students’ interest and intuition in quantum information science. *IEEE Trans. Educ.* 66, 422–433. doi: 10.1109/TE.2023.3241101
- Kaw, A., Lim, G. T., and Clark, R. M. (2024). Reflective questions: promoting metacognition through discussion board prompts. *J. High. Educ. Theory Pract.* 24, 161–175. doi: 10.33423/jhetp.v24i8.7238
- Keebaugh, C., Marshman, E., and Singh, C. (2024). Challenges in sense making and reasoning in the context of degenerate perturbation theory in quantum mechanics. *Phys. Rev. Phys. Educ. Res.* 20:020139. doi: 10.1103/PhysRevPhysEducRes.20.020139
- Khatib, E. (2024) Bridging theory and practice: revolutionizing STEM education with Jupyter. *INTED2024 Proceedings* 5984–5994. Valencia: IATED
- Kilpeläinen-Pettersson, J., Koskinen, P., Lehtinen, A., and Hirvonen, P. E. (2025). Cooperative learning in higher education physics—a systematic literature review. *Int. J. Sci. Math. Educ.* 23. doi: 10.1007/s10763-024-10538-3
- Kraus, S. F. (2024). The method of observation in science education: characteristic dimensions from an educational perspective. *Sci. Educ.* 33, 1033–1068. doi: 10.1007/s11191-023-00422-x
- Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A., and van Joolingen, W. R. (2017). Insights into teaching quantum mechanics in secondary and lower undergraduate education. *Phys. Rev. Phys. Educ. Res.* 13:010109. doi: 10.1103/PhysRevPhysEducRes.13.010109
- Kumar, S. (2024). Inculcating interest and quest for knowledge in physics at secondary level education. *Int. J. Adv. Eng. Manag.* 6, 476–480. doi: 10.35629/5252-0604476480
- Levy, J., and Singh, C. (2025). Hands-on quantum: teaching core quantum concepts with Bloch cubes. *Phys. Teach.* 63, 85–89. doi: 10.1119/5.0221594
- Lewis, E. B., Rivero, A. M., Lucas, L. L., Musson, A. A., and Helling, B. A. (2021). Setting empirically informed content knowledge policy benchmarks for physical science teaching. *J. Res. Sci. Teach.* 58, 1385–1417. doi: 10.1002/tea.21709
- Lichtenberger, A., Hofer, S. I., Stern, E., Edelsbrunner, P. A., Schumacher, R., and Sieber, V. (2025). Enhanced conceptual understanding through formative assessment: results of a randomized controlled intervention study in physics classes. *Educ. Assess. Eval. Account.* 37, 5–33. doi: 10.1007/s11092-024-09445-6
- Loviseti, L., and Giliberti, M. (2023). Inducing the construction of formal axioms of quantum mechanics and fostering their comprehension by high school students: the effectiveness of a conceptual approach. *Nuovo Cim.* 46:200. doi: 10.1393/ncc/i2023-23200-1
- Loviseti, L., Melli, E., and Giliberti, M. (2024). The elegance of quantum mechanics: a didactic path for high school. *J. Phys. Conf. Ser.* 2750:e012022. doi: 10.1088/1742-6596/2750/1/012022
- Maeng, J. L., and Bell, R. L. (2015). Differentiating science instruction: secondary science teachers’ practices. *Int. J. Sci. Educ.* 37, 2065–2090. doi: 10.1080/09500693.2015.1064553
- Majidy, S. 2024 Addressing misconceptions in university physics: a review and experiences from quantum physics educators arXiv [Preprint] doi: 10.48550/arXiv.2405.20923
- Mammino, L. (2023). Maximizing advantages and minimizing misinterpretation risks when using analogies in the presentation of chemistry concepts: a design challenge. *Phys. Sci. Rev.* 9, 2195–2220. doi: 10.1515/psr-2022-0318
- Michelini, M., and Stefanel, A. (2023). “Research studies on learning quantum physics” in The international handbook of physics education research: learning physics. eds. M. F. Taşar and P. R. L. Heron (Melville, NY: AIP Publishing LLC).
- Montagnani, S., Stefanel, A., Chiofalo, M. L. M., Santi, L., and Michelini, M. (2023). An experiential program on the foundations of quantum mechanics for final-year high-school students. *Phys. Educ.* 58:035003. doi: 10.1088/1361-6552/ab5da
- Morgan, P. (2022). The collapse of a quantum state as a joint probability construction. *J. Phys. A Math. Theor.* 55:254006. doi: 10.1088/1751-8121/ac6f2f
- Mulder, R. A. (2014). The measurement problem, decoherence and education (Tesis, Utrecht University). *Found. Phys.* 46:999. doi: 10.1007/s10701-016-9999-5
- Nautiyal, V. V., Salvador, E. E. P., Braña, X. R. O., and Prudente, M. S. (2025). Enhancing high school students’ understanding and attitude towards quantum mechanics through discipline-culture framework and cognitive apprenticeship. *Res. Sq.* 12:104. doi: 10.21203/rs.3.rs-5323874/v1

- Nikolaus, P., Džeralija, M., and Weber, I. (2024). Investigating students' conceptual knowledge of quantum physics to improve the teaching and learning process. *Educ. Sci.* 14:1113. doi: 10.3390/educsci14101113
- Nita, L., Mazzoli Smith, L., Chancellor, N., and Cramman, H. (2021). The challenge and opportunities of quantum literacy for future education and transdisciplinary problem-solving. *Res. Sci. Technol. Educ.* 41, 564–580. doi: 10.1080/02635143.2021.1920905
- Ole, F. C., and Gallos, M. R. (2023). Impact of formative assessment based on feedback loop model on high school students' conceptual understanding and engagement with physics. *J. Turkish Sci. Educ.* 20, 333–355. doi: 10.36681/tused.2023.019
- Onorato, P., Di Mauro, M., and Malgieri, M. (2024). Investigating the beliefs of experts on teaching quantum physics at secondary schools: key concepts, topics, and fundamentals. *Phys. Educ.* 59:025006. doi: 10.1088/1361-6552/ad2106
- Otero, M. R., and Fanaro, M. A. (2019). "Emotions, feelings, and conceptualizations in the didactics of physics" in Science education research in Latin America. ed. A. Adúriz-Bravo (Leiden: Brill).
- Paneru, D., Cohen, E., Fickler, R., Boyd, R. W., and Karimi, E. (2020). Entanglement: quantum or classical? *Rep. Prog. Phys.* 83:064001. doi: 10.1088/1361-6633/ab85b9
- Patterson, Z., and Ding, L. (2025). Epistemic framing analysis of secondary students during instruction on quantum physics. *Phys. Rev. Phys. Educ. Res.* 21:010116. doi: 10.1103/PhysRevPhysEducRes.21.010116
- Pelton, J. N., and Madry, S. (2023). "Space systems, quantum computers, big data and sustainability: new tools for the United Nations sustainable development goals" in Artificial intelligence for SPACE: AI4SPACE. eds. M. Madi and O. Sokolova (Boca Raton FL: CRC Press).
- Pengelly, J., Whipp, P. R., and Malpique, A. (2024). A testing load: a review of cognitive load in computer and paper-based learning and assessment. *Technology, Pedagogy and Education*. doi: 10.1080/1475939X.2024.2367517
- Perron, J. K., Deleone, C., Sharif, S., Carter, T., Grossman, J. M., Passante, G., et al. 2021 Quantum undergraduate education and scientific training arXiv [Preprint]. doi: 10.48550/arXiv.2109.13850
- Pollock, S., Passante, G., and Sadaghiani, H. (2023). Adaptable research-based materials for teaching quantum mechanics. *Am. J. Phys.* 91, 40–47. doi: 10.1119/5.0109124
- Pospiech, G., Michelini, M., and Enyeart, B. (2021). "The role of mathematics in teaching quantum physics at high school" in Teaching-learning contemporary physics. eds. B. Jarosievitz and C. Sükösd, Challenges in Physics Education (Berlin: Springer), 53–68.
- Prahani, B. K., Susiawati, E., Deta, U. A., Lestari, N. A., Yantidewi, M., Jauharyah, M. N. R., et al. (2021). Profile of students' physics problem-solving skills and the implementation of inquiry (free, guided, and structured) learning in senior high school. *J. Phys. Conf. Ser.* 1747:012012.
- Rasjid, Y., and Bahar, I. (2023). Application of a collaborative learning model accompanied by quantum learning strategies in improving class VIII science biology learning outcomes at junior high school 2 Satap Balla. *ARRUS J. Soc. Sci. Humanit.* 3, 385–390. doi: 10.35877/soshum1963
- Renken, M., Peffer, M., Otrell-Cass, K., Girault, I., and Chiocarriello, A. (2016). "Simulations as scaffolds in science education" in SpringerBriefs in educational communications and technology (Berlin: Springer).
- Rodriguez, L. V., van der Veen, J. T., Anjewierden, A., van den Berg, E., and de Jong, T. (2020). Designing inquiry-based learning environments for quantum physics education in secondary schools. *Phys. Educ.* 55:e065026. doi: 10.1088/1361-6552/abb346
- Rodriguez, L. V., van der Veen, J. T., and de Jong, T. (2025). Role of analogies with classical physics in introductory quantum physics teaching. *Phys. Rev. Phys. Educ. Res.* 21:e010108. doi: 10.1103/PhysRevPhysEducRes.21.010108
- Schermerhorn, B. P., Corsiglia, G., Sadaghiani, H., Passante, G., and Pollock, S. (2022). From Cartesian coordinates to Hilbert space: supporting student understanding of basis in quantum mechanics. *Phys. Rev. Phys. Educ. Res.* 18:e010145. doi: 10.1103/PhysRevPhysEducRes.18.010145
- Serbin, K. S., and Wawro, M. (2024). The inextricability of students' mathematical and physical reasoning in quantum mechanics problems. *Int. J. Res. Undergrad. Math. Educ.* 10, 57–86. doi: 10.1007/s40753-022-00174-z
- Shrestha, P. S., Perlman, T. T., and Shaver, S. R. (2023). Addressing learning difficulties in junior high school physics education: insights for curriculum development and teaching strategies. *Jurnal Ilmu Pendidikan Dan Humaniora* 12, 108–120. doi: 10.35335/jiph.v12i2.35
- Song, C., Shin, S.-Y., and Shin, K.-S. (2023). Optimizing foreign language learning in virtual reality: a comprehensive theoretical framework based on constructivism and cognitive load theory (VR-CCL). *Appl. Sci.* 13:12557. doi: 10.3390/app132312557
- Stein, L. A. (2004). Achieving quantitative literacy: An urgent challenge for higher education. Washington, DC: Mathematical Association of America.
- Steffe, L. P., and Ulrich, C. (2020). "Constructivist teaching experiment" in Encyclopedia of mathematics education. ed. S. Lerman (Berlin: Springer).
- Sun, Q., Zhou, S., Chen, R., Feng, G., Cheung, K. T., Li, J., et al. (2024). From computing to quantum mechanics: accessible and hands-on quantum computing education for high school students. *EPJ Quantum Technol.* 11:58. doi: 10.1140/epjqt/s40507-024-00271-9
- Sweller, J. (2023a). "Cognitive load theory: what we learn and how we learn" in Learning, design, and technology. eds. J. M. Spector, B. B. Lockee and M. D. Childress (Berlin: Springer).
- Sweller, J. (2023b). The development of cognitive load theory: replication crises and incorporation of other theories can lead to theory expansion. *Educ. Psychol. Rev.* 35:95. doi: 10.1007/s10648-023-09817-2
- Syafitri, D., Dari, A., Setiawan, I., and Matrasulov, J. (2024). Introduction of quantum system, step potential and barrier potential to class X students of SMA Budi Utomo Bengkulu City. *Aktual* 2, 1–7. doi: 10.58723/aktual.v2i1.119
- Taihuttu, J., Batlolona, J. R., Wattimena, H. S., Jamaludin, J., Silahooy, S., and Akyuwen, F. (2024). Analysis of students' cognitive physics learning outcomes on the material of substances and their forms using think-pair-share. *J. Sci. Educ.* 5, 178–185. doi: 10.29303/jossed.v5i2.9711
- Tarng, W., and Pei, M.-C. (2023). Application of virtual reality in learning quantum mechanics. *Appl. Sci.* 13:10618. doi: 10.3390/app131910618
- Taşar, M. F., and Heron, P. R. L. (2023). The international handbook of physics education research: learning physics. Melville, NY: AIP Publishing.
- Theodoropoulou, K., Xenakis, A., Antonis, K., Christopoulos, A., Palaigeorgiou, G., Kalogiannakis, M., et al. (2024). A survey on quantum literacy within gamification in science education. *Int. J. Adv. Multidiscip. Res. Stud* 5, 1137–1149. doi: 10.36227/techxiv.172792642.24672504/v1
- Tóth, K., Michelini, M., and Bitzenbauer, P. (2024). From light polarization to quantum physics: supporting lower secondary school students' transition from gestalt to functional thinking. *Eurasia journal of mathematics, science and technology. Education* 20:em2449. doi: 10.29333/ejmste/14587
- van Nooijen, C. C. A., de Koning, B. B., Brammer, W. M., and van Gog, T. (2024). A cognitive load theory approach to understanding expert scaffolding of visual problem-solving tasks: a scoping review. *Educ. Psychol. Rev.* 36:12. doi: 10.1007/s10648-024-09848-3
- Velentzas, A., Halkia, K., and Skordoulis, C. (2007). Thought experiments in the theory of relativity and in quantum mechanics: their presence in textbooks and in popular science books. *Sci. Educ.* 16, 353–370. doi: 10.1007/s11191-006-9030-1
- Weber, J., and Wilhelm, T. (2020). The benefit of computational modelling in physics teaching: a historical overview. *Eur. J. Phys.* 41:034003. doi: 10.1088/1361-6404/ab7a7f
- Weissman, E. Y., Merzel, A., Katz, N., and Galili, I. (2022). Phenomena and principles: presenting quantum physics in a high school curriculum. *Physics* 4, 1299–1317. doi: 10.3390/physics4040083
- Winarto, W., Kristyaningrum, D. H., Rahayu, R., Hayu, W. R. R., Jumini, S., and Dewi, N. D. L. (2024). Science teachers' perceptions of differentiated learning: a survey study. *Multidiscip. Sci. J.* 7:2025101. doi: 10.31893/multiscience.2025101
- Wong, J. H. C. (2024). Integrating quantum mechanics and the advanced observer model: a new paradigm for reality construction. *J. Quantum. Inf. Sci.* 14, 91–102. doi: 10.4236/jqis.2024.144008
- Worku, D. T., Ejigu, M. A., Gebremeskal, T. G., and Kassa Gogie, T. (2025). Assessing the impact of multiple representations based instruction integrated with formative assessment practice on secondary school students' problem-solving performance in physics. *Res. Sci. Technol. Educ.*, 1–26. doi: 10.1080/02635143.2025.2469062
- Yonai, E., and Blonder, R. (2025). "Powered by emotions": exploring emotion induction in out-of-school authentic science learning. *J. Res. Sci. Teach.* 62, 553–575. doi: 10.1002/tea.21982
- Zambrano, J. R., Kirschner, P. A., and Kirschner, F. 2019 How cognitive load theory can be applied to collaborative learning: collaborative cognitive load theory S. Tindall-Ford, S. T. Poghosyan and Merriënboer J. G. van Advances in cognitive load theory 84–93 Milton Park: Routledge
- Zohar, A. R., and Levy, S. T. (2021). From feeling forces to understanding forces: the impact of bodily engagement on learning in science. *J. Res. Sci. Teach.* 58, 1203–1237. doi: 10.1002/tea.21698
- Zuccarini, G., and Malgieri, M. (2024). Modeling and representing conceptual change in the learning of successive theories. *Sci. Educ.* 33, 717–761. doi: 10.1007/s11191-022-00397-1