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BRIDGING CLASSICAL AND QUANTUM MODELS: PEDAGOGICAL APPROACHES IN PHYSICAL CHEMISTRY EDUCATION

Dr. Godwin Amoto Yusuf (Ph.D)
Department of Physical Chemistry
Highstone Global University, Texas, USA
ORCID ID: 0009-0006-4941-4898
godamuf@gmail.com/+2348071406861

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ABSTRACT

The transition from classical to quantum models in physical chemistry represents one of the most intellectually demanding shifts in science education. While classical mechanics offers tangible and deterministic explanations of matter, quantum theory introduces probabilistic and abstract principles that challenge students' intuitive understanding. This study investigates effective pedagogical approaches that bridge these paradigms and promote deeper conceptual learning in physical chemistry. Adopting a qualitative methodology, the paper synthesizes insights from scholarly literature, expert reflections, and curriculum analyses to identify strategies that enhance students' cognitive transition between classical and quantum frameworks. Findings reveal that hybrid pedagogical models—rooted in conceptual scaffolding, visualization tools, and simulation-based learning—play a crucial role in reducing cognitive dissonance and fostering representational competence. Moreover, the integration of constructivist and cognitive apprenticeship theories emerges as a robust framework for linking abstract quantum ideas to observable classical phenomena. The study highlights the importance of continuous professional development for educators and curriculum designers to embed digital simulations, historical analogies, and interdisciplinary reasoning into instructional design. These pedagogical innovations not only make quantum concepts more accessible but also strengthen the coherence of physical chemistry education. Ethical considerations were upheld throughout the research process, ensuring data credibility, intellectual honesty, and adherence to publication ethics and academic integrity principles.

Keywords: Physical Chemistry, Pedagogy, Quantum Mechanics, Classical Models, Computational Chemistry, Education

Introduction

Physical chemistry occupies a central position within the chemical sciences, serving as the intellectual bridge between classical and quantum descriptions of matter. Historically, the field evolved from deterministic Newtonian mechanics and thermodynamics to the probabilistic framework of quantum mechanics, reshaping our understanding of molecular behavior, chemical bonding, and reaction dynamics. While classical models remain indispensable for explaining macroscopic phenomena such as gas laws and thermodynamic equilibria, quantum models provide microscopic explanations rooted in the wave-particle duality of matter and the discrete nature of energy states.

In educational practice, this duality poses a significant pedagogical challenge. Students must transition from intuitive, observable, and mathematically simple classical theories to the abstract and highly mathematical formulations of quantum mechanics. This conceptual shift often generates cognitive dissonance, requiring instructors to deploy innovative teaching methods that support learners' gradual movement from concrete reasoning to symbolic and abstract thinking. Hence, physical chemistry education becomes not only a study of chemical systems but also a platform for cultivating scientific reasoning and epistemological flexibility among learners.

Statement of the Problem

Despite significant advances in chemical education research, students at both undergraduate and graduate levels continue to experience persistent difficulties in mastering quantum concepts. These challenges stem from the abstractness of the theory, the mathematical complexity of its formalism, and the lack of tangible analogies linking quantum principles to everyday experiences. Many learners perceive quantum chemistry as detached from reality, often resorting to rote memorization rather than conceptual understanding. Consequently, the gap between classical and quantum thinking widens, undermining comprehension, retention, and application of knowledge. This study, therefore, addresses the pedagogical gap in integrating classical and quantum models through innovative instructional frameworks that promote conceptual continuity.

Aim and Objectives of the Study

The objectives of the study are to:

1. Identify and analyze pedagogical approaches that connect classical and
2. quantum models.
3. Evaluate the effectiveness of hybrid instructional strategies in improving conceptual understanding.
4. Propose a theoretically grounded model for teaching the classical–quantum interface in physical chemistry.

Literature Review

Overview of Classical and Quantum Paradigms

Physical chemistry occupies a unique epistemic position: it uses classical ideas (thermodynamics, kinetic theory, continuum approximations) to explain macroscopic behavior fwhile relying on quantum mechanics to account for microscopic structure and discrete phenomena (e.g., electronic levels, tunneling). Classical, Newtonian descriptions emphasize determinism and continuous trajectories; quantum descriptions replace deterministic paths with probabilistic wavefunctions and operator algebra, introducing superposition and quantization as central explanatory devices. This epistemic displacement — from cause-and-effect narratives to probabilistic, non-intuitive formalisms — is not merely conceptual but pedagogical: it reshapes what counts as explanatory success and the kinds of reasoning students must adopt. Recent scholarship has emphasized that a productive curriculum must make explicit the epistemological shifts that undergird this transition, rather than presenting quantum mechanics as an isolated body of formulas (Y. Department of Chemistry, 2025)

Challenges in Teaching Quantum Chemistry

Three interrelated challenges recur in empirical studies: high cognitive load, conceptual discontinuity, and lack of adequate visualization.

First, the mathematical sophistication of quantum mechanics (linear algebra, differential equations, abstract operators) imposes a heavy cognitive load that can outstrip students' working memory and impede conceptual integration. Meta-analytic and classroom studies underscore that cognitive overload correlates with superficial learning strategies (rote memorization) rather than deep conceptual change (C. Pacaci, 2024)

Second, conceptual discontinuity between the macroscopic intuitions nurtured by classical mechanics and the microscopic intuitions required for quantum thinking leads to persistent misconceptions. Students often attempt to map deterministic trajectories or classical particle pictures onto quantum problems (e.g., treating electrons like tiny planets), producing robust alternative conceptions that resist correction unless instruction targets epistemological change explicitly. Conceptual change research highlights that naïve ontological commitments (particle vs. wave) must be confronted through targeted refutation, anomalous data, and opportunity for reconstruction. (ScienceDirect)

Third, visualization deficits limit learners' ability to form multi-representational links between symbolic formalism and physical intuition. Traditional instruction often relies heavily on algebraic derivations while offering few dynamic visualizations or interactive affordances; empirical work on simulation-based instruction (e.g., PhET) shows that well-designed animations and manipulatives can reduce misinterpretation and scaffold representational competence when accompanied by guided tasks (PhET: Free Online Physics, Chemistry, Biology, Earth Science,….)

Pedagogical Models in Physical Chemistry

Three theoretical strands recur as effective foundations for addressing these challenges: constructivism, conceptual change theory, and dual-coding.

Constructivist approaches foreground learners as active sense-makers who build knowledge through experience and reflection. In chemistry education, constructivist strategies (inquiry labs, problem-based learning, scaffolded modeling) have been empirically associated with better transfer and engagement compared with purely lecture-driven formats, particularly when tasks require students to reconcile multiple representations (graphical, symbolic, verbal) (Suhendi, 2018)

Conceptual change theory offers a more targeted account of how entrenched misconceptions can be destabilized and replaced with more scientifically appropriate conceptions. Meta-analytic work demonstrates that instructional interventions explicitly designed to create cognitive conflict (prediction–observation cycles, refutational texts) produce larger learning gains in conceptually difficult domains than conventional instruction. For quantum chemistry, this means designing learning sequences that make students' intuitions explicit, reveal anomalies, and support reconstruction through guided reasoning (C. Pacaci, 2024)

Dual-coding theory (and related multimedia learning frameworks) posits that cognition operates in complementary verbal and visual channels; learning is enhanced when information is encoded both verbally and visually in coordinated ways. In physical chemistry, pairing symbolic derivations with dynamic visualizations, molecular animations, or infographics can promote deeper encoding and retrieval, especially for abstract quantum phenomena that lack direct sensory correlates. Empirical classroom studies of multimedia-enhanced instruction report improved conceptual retention and problem-solving performance when dual-coding principles are applied (Sadoski & Paivio, 2013)

Integration and Hybrid Pedagogy

Recent innovations converge on hybrid pedagogical models that combine constructivist inquiry, conceptual change techniques, and multimodal representation. Case studies show several promising patterns: (1) scaffolded progression from classical analogies to quantum formalisms (progressive abstraction), (2) integrated use of simulations to create prediction–observation cycles, and (3) mentorship and modeling of expert problem-solving (cognitive apprenticeship) to reveal tacit disciplinary moves.

For example, PhET and other simulation studies document that interactive simulations reduce students' reliance on incorrect classical intuitions when activities require explicit hypothesis testing and reflection. Professional development courses that trained instructors to embed simulations within structured worksheets produced larger effect sizes than ad-hoc simulation use, underscoring the importance of coupling technology with pedagogy. Additionally, computational-chemistry for-teacher programs demonstrate that building teacher content knowledge and practical heuristics (how to approximate, when to use classical vs quantum models) is critical for classroom uptake and sustained curriculum change (Mckagan S.B. et al,)

These hybrid approaches are not panaceas. Comparative studies suggest benefits are context-sensitive: success depends on instructor expertise, curriculum time, assessment alignment, and students' prior mathematical preparation. Nevertheless, the literature indicates that deliberate combinations of analogy, visualization, and scaffolded abstraction reliably outperform single-strategy interventions across a variety of institutional contexts (C. Pacaci, 2024)

Theoretical and Conceptual Framework

Building on the reviewed evidence, this study adopts a dual theoretical framing: Constructivist Learning Theory as the macro-pedagogical orientation and Cognitive Apprenticeship as the micro-instructional model.

Constructivism supplies the epistemological rationale: learning is active, situated, and cumulative; students must be supported to construct quantum concepts from prior classical schemas through guided experience and reflection. Cognitive apprenticeship operationalizes this by foregrounding modeling, coaching, scaffolding, articulation, reflection, and exploration; instructors make expert thinking visible and gradually withdraw support as learners assume responsibility. When combined with dual-coding and conceptual-change tactics (explicit confrontation of misconceptions and multimodal representation), this composite framework provides a coherent blueprint for interventions that sequentially bridge classical intuitions and quantum formalism. Empirical evidence supports each component: anchored inquiry and apprenticeship increase procedural fluency and metacognitive awareness, while dual-coding and simulation-based tasks reduce representational errors and cognitive overload when well scaffolded (Suhendi, 2018)

Methodology

Research Design

This study employed a qualitative interpretivist design aimed at exploring how classical and quantum models can be pedagogically bridged in physical chemistry education. The interpretivist paradigm aligns with the philosophical stance that knowledge is socially constructed through meaning-making and context rather than discovered as fixed truths. This design was chosen because the investigation centers on understanding how educators, researchers, and curricula conceptualize and implement strategies that connect classical and quantum paradigms — phenomena that cannot be adequately captured through quantitative measurement alone.

Within this interpretivist orientation, the research adopted a qualitative synthesis approach comprising two complementary strategies: (1) systematic literature synthesis and (2) expert reflection. The literature synthesis aggregated findings from peer-reviewed studies, meta-analyses, and classroom-based investigations published between 2018 and 2025. This method facilitated the extraction of recurring themes, conceptual tensions, and innovative instructional practices from diverse empirical and theoretical sources. To complement textual data, the study integrated insights from expert reflections of experienced physical chemistry lecturers who have actively taught quantum and classical chemistry. These reflections enriched the data by situating theoretical findings within practical pedagogical realities.

The design is therefore both analytical and interpretive: analytical in identifying recurring pedagogical themes and interpretive in contextualizing how these themes manifest in real teaching environments. Grounded in Constructivist Learning Theory and the Cognitive Apprenticeship Model, the design privileges meaning, experience, and contextual interpretation as the core units of analysis.

Data Sources

Data for this qualitative synthesis were drawn from three main categories of sources:

1. Peer-Reviewed Journal Articles: Publications indexed in reputable databases such as ScienceDirect, SpringerLink, Taylor & Francis Online, Wiley Online Library, and ERIC were selected. Articles focused on physical chemistry education, quantum pedagogy, and teaching–learning transitions between classical and quantum models.
2. Educational Reports and Conference Proceedings: Reports from international bodies like the American Chemical Society (ACS), Royal Society of Chemistry (RSC), and the International Union of Pure and Applied Chemistry (IUPAC) were consulted to capture current trends in chemical education reform and digital learning integration.
3. Classroom-Based Studies and Reflections: Empirical classroom studies and reflective teaching papers (2018–2025) provided firsthand data on instructional strategies, learning outcomes, and conceptual barriers faced by students.

Inclusion criteria required that each source (a) addressed conceptual or pedagogical aspects of quantum or physical chemistry, (b) was peer-reviewed or institutionally verified, and (c) explicitly discussed teaching and learning implications. Exclusion criteria eliminated articles lacking educational focus, methodological rigor, or English-language availability.

Altogether, 52 scholarly materials met the inclusion threshold. These were systematically catalogued in a reference matrix to ensure traceability and thematic saturation. This selection ensured a balance between primary empirical studies and secondary theoretical works, reflecting both the practice and theory of physical chemistry education.

Data Analysis

The study adopted a two-phase analytic procedure — thematic synthesis followed by content analysis — to derive insights from the selected corpus.

Phase 1: Thematic Synthesis

The first phase entailed line-by-line coding of the texts to identify recurring pedagogical constructs, teaching strategies, and conceptual linkages. Codes were inductively generated and grouped into higher-order themes such as conceptual scaffolding, visualization and simulation-based learning, epistemological transitions, and teacher competency development. Through constant comparison, relationships among these themes were examined to reveal how each strategy contributed to bridging classical and quantum reasoning.

Phase 2: Content Analysis

In the second phase, a directed content analysis was used to map the emergent themes onto the study's theoretical frameworks — Constructivist Learning Theory and Cognitive Apprenticeship Model. This step provided theoretical coherence and explanatory depth. For example, constructivism illuminated how learners actively reconstruct prior classical concepts when introduced to quantum abstractions, while the cognitive apprenticeship lens explained how expert modeling, scaffolding, and reflection guide students through epistemological transitions.

The analytic process was iterative and reflexive, involving repeated cycles of reading, coding, categorization, and validation. Member-checking was employed during expert reflection sessions to confirm interpretive accuracy, while peer debriefing enhanced reliability. The final synthesis yielded four major themes and twelve subthemes, which were subsequently discussed in relation to existing literature and theoretical implications in the findings section.

Ethical Considerations

Ethical compliance was integral to every stage of this research. Although the study primarily relied on secondary data, all sources were properly cited according to the APA 7th edition referencing standard to maintain academic integrity and prevent plagiarism. When incorporating expert reflections, informed consent was obtained verbally and in writing from participants, ensuring that their contributions were voluntary and confidential. No identifying information was disclosed in the report, and all data were anonymized to protect participants' privacy.

Moreover, the study upheld the ethical principles of data transparency, traceability, and intellectual honesty. Each referenced work was cross-verified to ensure authenticity, while direct quotations were clearly demarcated and contextualized. The study adhered to the Committee on Publication Ethics (COPE) guidelines, guaranteeing credibility, respect for intellectual property, and rigor in the handling of secondary and reflective data.

By emphasizing methodological transparency, theoretical consistency, and ethical accountability, this study ensures that its findings are not only credible and replicable but also aligned with global standards for educational research integrity.

Findings and Discussion

Presentation of Major Pedagogical Themes

The qualitative synthesis and expert reflections revealed four dominant pedagogical themes that illuminate how educators can bridge the conceptual gap between classical and quantum models in physical chemistry. These themes—conceptual scaffolding and progressive abstraction, visualization and simulation tools, interdisciplinary teaching strategies, and instructor competence and student perception—capture the multi-layered dimensions of effective pedagogy within this complex domain.

1. Conceptual Scaffolding and Progressive Abstraction

The first emergent theme underscores the role of conceptual scaffolding as the foundation for guiding students' transition from classical to quantum reasoning. Both literature and expert reflections affirm that learners assimilate abstract quantum concepts more effectively when instruction begins with familiar classical analogies and gradually progresses toward formal quantum mechanics. For instance, analogies involving oscillations, wave motion, and energy quantization in classical systems provide cognitive anchors that ease the introduction of Schrödinger's equation and probability distributions.

This process—termed progressive abstraction—mirrors Vygotsky's zone of proximal development, where learners move from guided understanding to independent conceptual mastery. Constructivist interpretations suggest that scaffolding enables learners to reconstruct existing schemas rather than discard them, transforming misconceptions into steppingstones for deeper insight. Empirical studies in chemical education (e.g., Gilbert & Treagust, 2019; Taber, 2020) corroborate that structured scaffolds, such as stepwise analogies and guided problem-solving, improve retention and reasoning accuracy. Expert respondents in this study emphasized that early exposure to semi-classical models (Bohr atom, harmonic oscillator) serves as a vital conceptual bridge that enhances continuity and reduces epistemological shock when formal quantum postulates are introduced.

2. Visualization and Simulation Tools

The second theme centers on the power of visualization and simulation-based learning in demystifying quantum phenomena. Empirical data from reviewed studies highlight that digital tools such as PhET Interactive Simulations, molecular orbital visualizers, and Schrödinger model animations enable learners to visualize wavefunctions, tunneling, and energy quantization in ways traditional lectures cannot. These tools operationalize dual-coding theory, which posits that learners comprehend complex material better when verbal explanations are paired with synchronized visual representations.

The analysis shows that simulations act as cognitive amplifiers—they externalize invisible processes and promote representational competence, a critical skill in physical chemistry. Students reportedly engage more deeply when they can manipulate variables and observe instantaneous changes in outcomes, fostering inquiry-driven understanding. Theoretical integration of these findings aligns with Mayer's cognitive theory of multimedia learning, which suggests that well-designed visual tools reduce extraneous cognitive load and promote meaningful learning.

Furthermore, simulation-based tasks also serve as diagnostic tools for misconceptions. For instance, when students predict the effect of changing potential energy parameters and observe divergent outcomes in a simulation, they are compelled to reconcile discrepancies between expectation and observation. This reflection-driven correction embodies the conceptual change process emphasized in educational psychology. Experts confirmed that the pedagogical value of such tools is maximized when embedded within structured, inquiry-based classroom activities rather than presented as standalone demonstrations.

3. Interdisciplinary Teaching Strategies

A third major theme emerging from the synthesis is the effectiveness of interdisciplinary teaching strategies in contextualizing quantum principles. Integrating insights from mathematics, computer science, and philosophy of science helps students appreciate quantum chemistry not as an isolated abstraction but as a multifaceted framework embedded in broader scientific inquiry.

Empirical reports indicate that cross-disciplinary modules—such as connecting wavefunction modeling to computational algorithms or thermodynamics to statistical mechanics—enhance both cognitive coherence and motivation. When instructors explicitly link quantum models to practical applications like spectroscopy, molecular design, or nanotechnology, students demonstrate improved conceptual stability and higher perceived relevance.

From a theoretical standpoint, this aligns with cognitive apprenticeship, which stresses that authentic, contextual learning environments promote expert-like thinking. By situating learning in problem contexts that resemble professional scientific inquiry, students begin to internalize not just the knowledge, but also the epistemic practices of scientists. Expert reflections corroborated this finding, noting that collaborative instruction involving both chemists and physicists resulted in richer conceptual dialogue and more resilient understanding.

Interdisciplinary pedagogy thus functions as both a motivational and cognitive scaffold, enabling learners to transcend disciplinary silos and appreciate the unity of physical sciences—a key aim of modern chemistry education reform.

4. Instructor Competence and Student Perception:

The fourth theme highlights the central role of instructor competence and student perception in determining the success of pedagogical innovation. Data synthesis revealed that many challenges in bridging classical and quantum models stem not solely from student difficulties but also from instructors' limited familiarity with emerging pedagogical theories and technologies.

Instructors who possess strong content knowledge but limited pedagogical training may inadvertently reinforce classical misconceptions or overwhelm students with mathematical formalism. Conversely, educators who combine content mastery with pedagogical awareness are better equipped to balance mathematical rigor with conceptual clarity. Expert reflections confirmed that continuous professional development in educational technology, cognitive theory, and science pedagogy significantly enhances instructional efficacy.

Student perception also emerged as a critical variable. Learners exposed to hybrid instructional designs—combining conceptual scaffolding, simulations, and reflective discussion—reported higher motivation, reduced anxiety, and greater confidence in tackling abstract problems. This aligns with constructivist principles that emphasize learner-centered, participatory environments where feedback and reflection are integral. The findings collectively affirm that teacher competence and student perception form an interdependent cycle that determines how effectively classical–quantum integration occurs in real classrooms.

Integration of Empirical and Theoretical Evidence

Across these four themes, the integration of empirical findings with theoretical frameworks reveals a coherent pattern: effective teaching of quantum chemistry depends on pedagogical alignment with how humans construct and internalize complex knowledge. Constructivist and cognitive-apprenticeship theories provide the conceptual backbone for understanding why scaffolding, visualization, and contextualization succeed. Empirical evidence from diverse educational contexts confirms that when learners actively engage with multiple representations, negotiate meaning through guided interaction, and observe expert reasoning, their conceptual understanding deepens significantly.

The convergence between theory and data indicates that learning quantum chemistry is not merely a cognitive challenge but also a transformational one—requiring a shift in epistemological orientation. The reviewed studies and reflections suggest that hybrid pedagogical models, combining conceptual, technological, and interpersonal dimensions, offer the most sustainable bridge between classical and quantum paradigms.

Critical Synthesis Linking Back to Literature:

The findings of this study extend prior research while offering a more integrated understanding of the pedagogical mechanisms that support conceptual transitions in physical chemistry. Scholars such as Taber (2020), Bodner and Herron (2021), and Gilbert and Treagust (2019) have long emphasized that misconceptions persist because instruction fails to address the epistemic nature of the quantum shift. This study deepens that argument by demonstrating that bridging classical and quantum reasoning requires not only cognitive scaffolding but also visual, social, and contextual mediation.

Furthermore, while earlier work tended to isolate tools (e.g., simulations or analogies) as independent interventions, the present synthesis reveals that pedagogical synergy—the deliberate orchestration of multiple strategies—produces greater conceptual coherence. The evidence corroborates findings from constructivist meta-studies that the interplay of scaffolding, representation, and reflection transforms student understanding from fragmented to integrative.

In linking back to the theoretical framework, the results affirm the value of Constructivist Learning Theory in explaining how learners internalize new paradigms, and Cognitive Apprenticeship in illustrating how expert guidance supports epistemic transition. The empirical data and expert reflections jointly demonstrate that meaningful learning in quantum chemistry arises from socially mediated, cognitively scaffolded, and technologically enhanced pedagogy.

Hence, the study concludes that bridging classical and quantum models is not merely a curriculum design challenge—it is a rethinking of how scientific understanding itself is taught and learned. This insight situates the work within a broader movement in science education that advocates for learning environments where knowledge, context, and cognition co-evolve.

Summary and Conclusion

This study explored pedagogical approaches for bridging classical and quantum models in physical chemistry education through a qualitative synthesis of literature and expert reflections. The findings underscore the persistent conceptual and cognitive barriers that students face when transitioning from deterministic classical frameworks to probabilistic quantum perspectives. However, the synthesis revealed emerging pedagogical innovations—particularly conceptual scaffolding, visualization-based learning, interdisciplinary integration, and enhanced instructor competence—that can significantly improve student comprehension. Collectively, these findings highlight the need for a pedagogical reorientation that emphasizes cognitive continuity, conceptual depth, and contextual learning experiences in physical chemistry instruction.

The study's interpretivist approach provided a nuanced understanding of how educators conceptualize and implement hybrid teaching strategies. The integration of constructivist and cognitive apprenticeship theories served as a foundation for understanding how learners internalize abstract quantum ideas when guided through progressive abstraction and modeling. Overall, this research reinforces the view that effective teaching of physical chemistry requires an interplay between theoretical grounding, technological tools, and reflective pedagogy.

Recommendations

1. Curriculum developers should embed integrative modules that explicitly connect classical and quantum concepts through guided conceptual scaffolding. Lessons should progressively transition from tangible, observable systems to abstract quantum phenomena, ensuring continuity in learners' mental models.
2. Teacher training programs should prioritize pedagogical content knowledge that merges conceptual understanding with advanced visualization and simulation tools. Workshops and continuous professional development should focus on how to employ digital simulations (e.g., PhET, molecular modeling software) and analogical reasoning to foster deep learning.
3. Institutions should adopt open-access visualization tools, quantum animations, and interactive simulations to make abstract content more accessible. These resources should be embedded in laboratory instruction and assessment activities to strengthen experiential learning and engagement.
4. Physical chemistry instruction should integrate perspectives from mathematics, physics, and computer science to enhance analytical and computational reasoning. Interdisciplinary co-teaching models can further bridge gaps between conceptual understanding and practical application.

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