RESEARCH PROPOSAL

Supporting the Transition from Quantum Mechanics to Quantum Information Science through Formative Assessment and Interactive Tutorials

Master's Research Proposal

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Proposed Research Area: Physics Education Research / Quantum Information Science Education

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1. Executive Summary

This research proposal investigates how formative assessment and interactive tutorial-based curriculum design can support students' conceptual transition from introductory Quantum Mechanics (QM) to Quantum Information Science (QISE). The study is motivated by a persistent finding in Physics Education Research: many students can perform procedural calculations in quantum topics without developing a stable conceptual understanding of quantum states, measurement, superposition, and entanglement. These conceptual difficulties become especially problematic when students encounter introductory QISE topics such as qubits, quantum measurement in computational bases, and entanglement-based reasoning.

The project proposes a mixed-methods study embedded in a Design-Based Research framework. It includes an initial diagnostic phase, the design and implementation of interactive tutorial modules, iterative cycles of formative assessment, and a research-informed curriculum redesign. The expected contribution is both theoretical and practical: a refined model for conceptual transition in quantum learning and a transferable instructional sequence for use in undergraduate QM and introductory QISE contexts.

2. Background and Rationale

Quantum Information Science has become an increasingly important component of contemporary STEM education due to its scientific relevance, technological applications, and connections to emerging quantum industries. However, students frequently approach QISE with unresolved misconceptions originating in introductory quantum mechanics. These misconceptions concern the meaning of quantum states, the role of measurement, the interpretation of superposition, and the conceptual structure of entanglement.

Research in quantum education has shown that conceptual difficulties are not merely isolated mistakes; they are often robust patterns of reasoning rooted in classical intuitions, fragmented mathematical knowledge, and weak coordination across multiple representations. For this reason, effective instruction must move beyond content coverage and focus on evidence-based conceptual support, iterative feedback, and curricular coherence.

3. Research Problem

Despite substantial literature on student difficulties in quantum mechanics and the growing body of work in QISE education, there remains a need for integrated instructional models that combine diagnostic assessment, formative assessment, interactive tutorials, and curriculum redesign. In particular, limited research has systematically examined how these elements can support the transition from foundational QM reasoning to introductory QISE learning.

4. Aim and Research Questions

General Aim: To investigate how formative assessment and interactive tutorial-based curriculum design can reduce conceptual difficulties and support students' transition from introductory quantum mechanics to quantum information science.

Research Questions:

RQ1. What misconceptions related to quantum states, measurement, superposition, and entanglement are most prevalent prior to instruction?

RQ2. How do these misconceptions manifest across conceptual, mathematical, and verbal representations?

RQ3. To what extent does an interactive tutorial sequence combined with formative assessment reduce these misconceptions?

RQ4. Which conceptual difficulties remain resistant after the intervention?

RQ5. Which curricular elements appear most effective for supporting the transition from QM to QISE?

5. Integrated Theoretical Framework

The theoretical foundation of this proposal combines five complementary perspectives: Physics Education Research, conceptual change and misconceptions, multiple representations in science learning, formative assessment, and Design-Based Research. Together, these perspectives provide a coherent basis for understanding why students struggle with quantum concepts, how instructional interventions should be designed, and how curricular redesign can be iteratively improved through empirical evidence.

Within this framework, misconceptions are treated as persistent and context-sensitive patterns of reasoning rather than as simple factual errors. Formative assessment is used as a mechanism for continuously eliciting student thinking, providing feedback, and informing instructional adaptation. Interactive tutorials are conceptualized as scaffolded learning environments that coordinate mathematics, diagrams, verbal explanations, and simulations. Finally, Design-Based Research offers the overarching logic for iteratively developing, testing, and refining the curricular sequence in authentic educational settings.

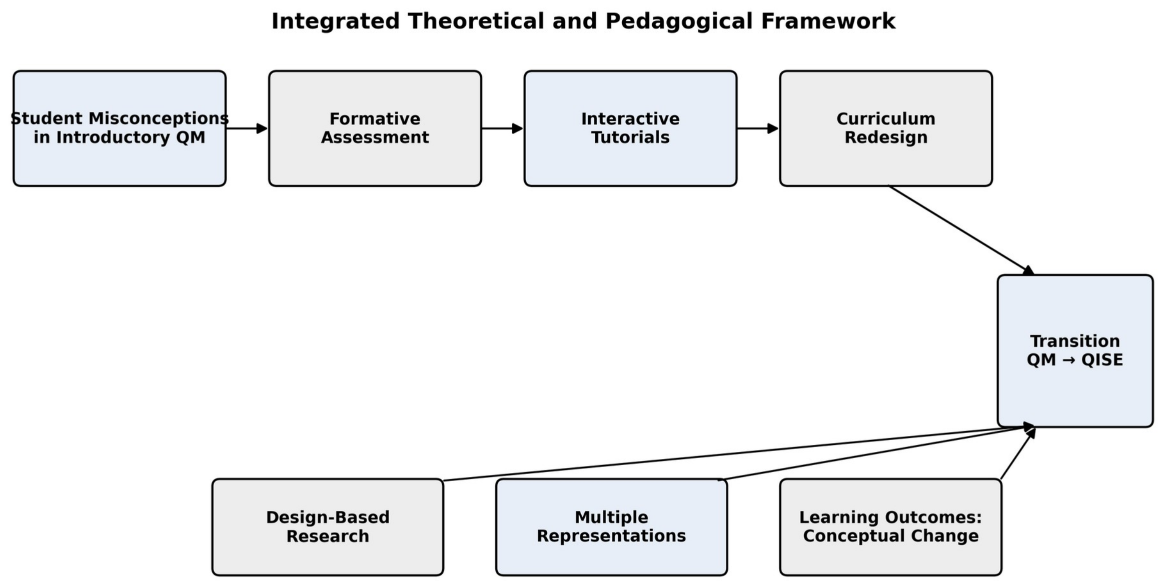

Figure 1. Integrated theoretical and pedagogical framework guiding the proposed study.

5.1 Physics Education Research (PER)

PER provides the disciplinary foundation for studying how students learn physics concepts and how instructional environments can be designed and evaluated. The project is aligned with the PER tradition of identifying recurring conceptual difficulties, developing research-based interventions, and using empirical evidence to improve teaching and learning.

5.2 Conceptual Change and Misconceptions

The study adopts a conceptual change perspective in which learning involves restructuring prior knowledge and replacing or refining non-productive explanatory models. In quantum learning, misconceptions often derive from inappropriate transfer of classical assumptions to non-classical contexts.

5.3 Multiple Representations

Students must coordinate symbolic, graphical, verbal, and visual representations to develop robust quantum reasoning. Difficulties often arise when learners can manipulate equations but cannot relate them to physical meaning.

5.4 Formative Assessment

Formative assessment is central to the proposal because it supports responsive teaching. Diagnostic questions, open-ended prompts, and tutorial checkpoints will be used to surface student reasoning and guide instructional feedback.

5.5 Design-Based Research

The intervention will be developed and refined using DBR principles. The research will therefore generate both local instructional improvements and broader design principles relevant to quantum education.

6. Review of Relevant Literature

The literature relevant to this proposal can be organized into four major strands: (a) studies on student difficulties in quantum mechanics; (b) research on tutorial-based and simulation-supported instruction; (c) work on assessment instruments in QM and QISE; and (d) emerging curricular studies that connect introductory QM to quantum information topics.

6.1 Key Literature Matrix

Topic	**Representative scholars / resources**	**Typical methods**	**Main implications**
Student difficulties in QM	Singh; Marshman; McKagan; Kohnle	Interviews, surveys, conceptual tests, qualitative analysis	Students often struggle with quantum states, measurement, wave-particle reasoning, and formalism-meaning coordination.
Interactive tutorials and QuILTs	Chandralekha Singh and collaborators	Iterative tutorial development, pre/post testing, think-aloud interviews	Interactive tutorials can reduce conceptual difficulties when grounded in evidence about student thinking.
Conceptual assessment in QM	QMCS, QMFPS, QMCA, QPCS	Instrument design, validation, psychometric analysis	Validated assessments provide a stronger basis for measuring conceptual change.
QISE assessments and curricula	QCCS, QISCIT, ACEQIS, Wilcox, Pollock, Meyer, Passante	Curriculum surveys, instrument development, pilot testing	The field is expanding rapidly, but coherent pathways from QM to QISE remain underdeveloped.

6.2 Research Gap

The central gap addressed by this proposal is the limited integration of misconception research, formative assessment, tutorial-based instruction, and curriculum redesign in studies focused on the transition from introductory QM to QISE. Existing literature provides strong foundations for each individual component, but fewer studies combine them into a single coherent instructional and research design.

7. Methodological Design

This study adopts a mixed-methods approach embedded within a Design-Based Research framework. The design combines quantitative evidence of conceptual change with qualitative evidence concerning the structure and evolution of student reasoning. Quantitative data will provide estimates of learning gains and conceptual shifts across key topics, whereas qualitative data will capture how students interpret quantum concepts, how they coordinate representations, and how their reasoning changes during the intervention.

The project will be organized into iterative stages including diagnostic assessment, tutorial design, pilot implementation, revised implementation, and curriculum redesign. This structure ensures that the intervention is not treated as a fixed product but as a research-informed instructional sequence subject to systematic refinement.

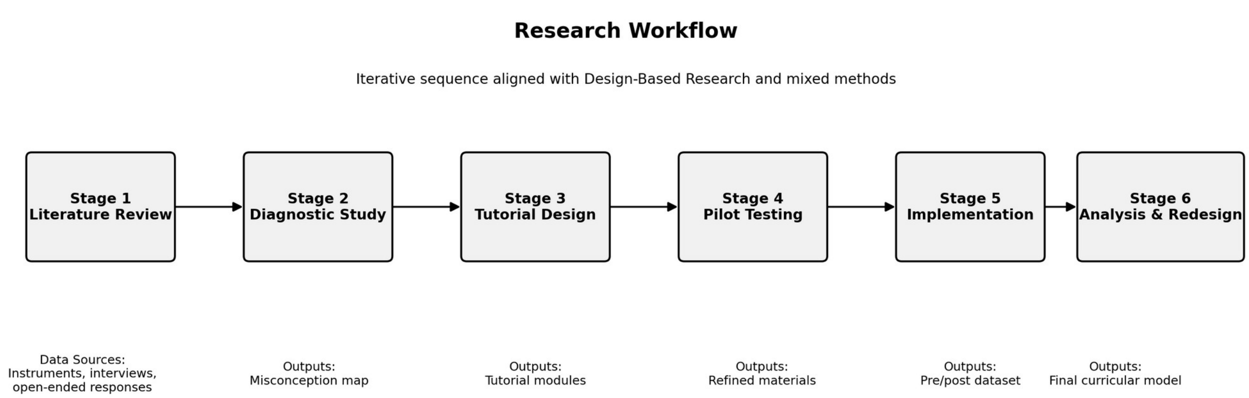

Figure 2. Research workflow across the major stages of the project.

7.1 Research Context and Participants

The study is designed for undergraduate students enrolled in an introductory Quantum Mechanics or Modern Physics course with a bridge module to Quantum Information Science. A projected sample of two course sections or two cohorts is recommended, ideally allowing comparison across a tutorial-based intervention condition and a conventional or comparison condition.

7.2 Conceptual Focus

The instructional sequence will focus on four core concepts: quantum states, measurement, superposition, and entanglement. These concepts were selected because they are foundational in introductory QM and also central to early QISE learning.

7.3 Instruments and Data Sources

Instrument / data source	Primary purpose	Type of data
Conceptual pre/post test (e.g., QMCS, QMFPS, QISCIT or adapted combination)	Measure conceptual change and identify persistent misconceptions	Quantitative
Open-ended conceptual tasks	Capture explanatory reasoning and representational coordination	Qualitative
Think-aloud interviews	Examine students' conceptual structures in depth	Qualitative
Formative tutorial checkpoints / quizzes	Provide in-process feedback and local evidence of learning	Quantitative + qualitative
Field notes and implementation records	Document instructional context and design adjustments	Qualitative

7.4 Instructional Intervention

The intervention will consist of a sequence of interactive tutorials informed by student difficulties documented in the literature and by evidence from the project's diagnostic phase. Each module will include conceptual prompts, opportunities for peer discussion, targeted feedback, multiple representations, and where appropriate, visualization or simulation-based tasks.

7.5 Data Analysis

Quantitative analysis: descriptive statistics, learning gains, effect size estimates, item-level analysis, and when appropriate, pre/post comparisons and group comparisons.

Qualitative analysis: coding of open-ended responses and interview transcripts, identification of misconception patterns, representational difficulties, and evidence of conceptual change. Inter-rater agreement procedures are recommended to strengthen analytic credibility.

Mixed-methods integration: quantitative and qualitative findings will be triangulated to generate a comprehensive account of how and why conceptual change occurs across the intervention.

7.6 Ethical Considerations

All stages of the study should be conducted under institutional ethical approval. Participation must be voluntary, confidentiality preserved, and all student data anonymized prior to analysis and dissemination.

8. Projected Research Timeline

The figure below presents a 24-month projected timeline for the project. It includes the sequence of research design, data collection, intervention, analysis, thesis writing, and article preparation.

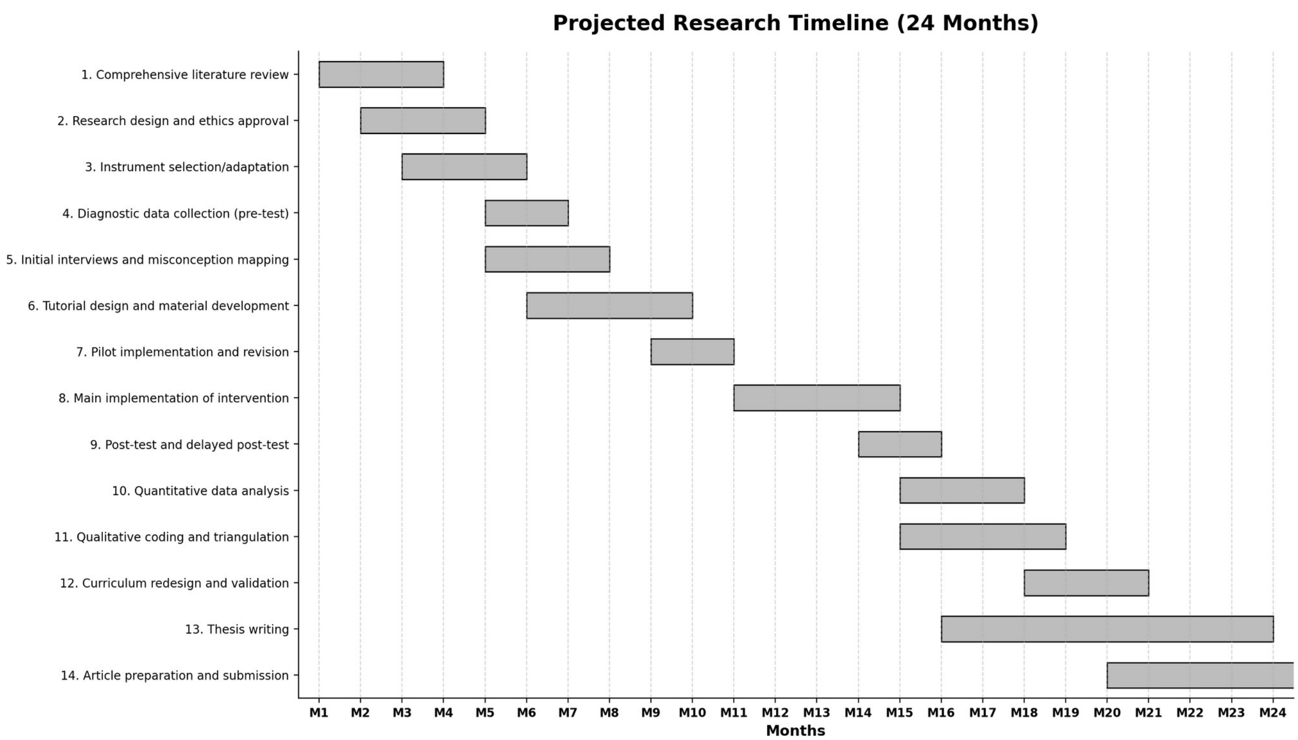

Figure 3. Projected 24-month research timeline with major stages and expected deliverables.

8.1 Stage-by-Stage Milestones

Stage	Months	Main objectives / expected outputs
Stage 1. Literature review	1–3	Build the theoretical framework, refine the research gap, and prepare

		the conceptual map of misconceptions.
Stage 2. Design and ethics preparation	2–4	Finalize the research design, prepare protocols, and obtain ethical approval.
Stage 3. Instrument selection/adaptation	3–5	Select or adapt assessment tools and prepare open-ended and interview tasks.
Stage 4. Diagnostic study	5–7	Administer pre-tests, collect baseline data, and conduct initial interviews.
Stage 5. Tutorial development	6–9	Design research-based tutorial modules and formative assessment tasks.
Stage 6. Pilot testing	9–10	Pilot the materials, identify implementation issues, and revise the modules.
Stage 7. Main intervention	11–14	Implement the tutorial sequence and collect instructional and assessment data.
Stage 8. Post-intervention assessment	14–15	Administer post-tests and, if possible, delayed post-tests.
Stage 9. Data analysis	15–18	Analyze quantitative and qualitative data and integrate findings.
Stage 10. Curriculum redesign	18–20	Produce the final curriculum model based on empirical evidence.
Stage 11. Thesis writing	16–23	Write the thesis chapters and prepare the final document.
Stage 12. Article preparation and submission	20–24	Prepare an international journal manuscript and submit it to a target journal.

9. Expected Contributions

A theoretically grounded model explaining how formative assessment and interactive tutorials can support students’ transition from introductory QM to QISE.

A misconception map focused on quantum states, measurement, superposition, and entanglement.

A research-based tutorial sequence suitable for adaptation in undergraduate quantum courses.

An empirically informed curriculum redesign model with practical and transferable implications.

A publication-oriented empirical study suitable for submission to a leading journal in Physics Education Research or Science/STEM Education.

10. Publication Strategy

The thesis is conceived as a publication-oriented research project. Its structure is intentionally designed so that the literature review, methodological design, and empirical results can be converted into one or more journal manuscripts. A primary target article may focus on the full intervention study, while secondary manuscripts may address the literature review, assessment adaptation, or design principles emerging from the curriculum redesign.

Potential journal targets: Physical Review Physics Education Research; Journal of Research in Science Teaching; International Journal of STEM Education; International Journal of Science Education; Research in Science Education.

11. Selected References

Black, P., & Wiliam, D. (1998). Assessment and classroom learning. Assessment in Education, 5(1), 7–74.

Cobb, P., Confrey, J., diSessa, A., Lehrer, R., & Schauble, L. (2003). Design experiments in educational research. Educational Researcher, 32(1), 9–13.

Kohnle, A., et al. (2015). Enhancing student learning of two-level quantum systems with interactive simulations. American Journal of Physics, 83(6), 560–566.

McKagan, S. B., Perkins, K. K., & Wieman, C. E. (2010). Design and validation of the Quantum Mechanics Conceptual Survey. Physical Review Special Topics—Physics Education Research, 6(2), 020121.

Passante, G., Pollock, S. J., Wilcox, B. R., & collaborators. ACEQIS curriculum materials and related scholarship in Quantum Information Science Education.

Sadaghiani, H. R., & Pollock, S. J. Quantum Mechanics Concept Assessment (QMCA) and associated validation work.

Singh, C. (2008). Interactive learning tutorials on quantum mechanics. American Journal of Physics, 76(4&5), 400–405.

Singh, C., Belloni, M., & Christian, W. (2006). Improving students' understanding of quantum mechanics. Physics Today, 59(8), 43–49.

Singh, C., & Marshman, E. (2015). Review of student difficulties in upper-level quantum mechanics. arXiv:1504.02056.

Wuttiprom, S., et al. (2009). Development and use of a conceptual survey in introductory quantum physics. International Journal of Science Education, 31(5), 631–654.

Zwickl, B. M., Finkelstein, N., & Lewandowski, H. J. (2013). The process of transforming an advanced lab course: Goals, curriculum, and assessments. American Journal of Physics, 81(1), 63–70.

Appendix A. Recommended Core Concepts and Indicators

Core concept	Typical misconception	Illustrative learning indicator
Quantum state	A quantum state is a hidden classical value.	Student explains a state as a mathematical representation with probabilistic measurement consequences.
Measurement	Measurement simply reveals a pre-existing value.	Student recognizes the state-update role of measurement.
Superposition	Superposition is equivalent to classical uncertainty.	Student differentiates coherent superposition from ignorance about definite states.
Entanglement	Entanglement is just strong classical correlation.	Student identifies non-factorizability and system-level description.