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Introduction to the special issue on teaching and learning quantum physics

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One of the strategies that have increased the quality of GIREP activities over the years is linked to the creation of Thematic Groups (GTG), which, in a qualified way, have proposed activities for discussion and in-depth analysis of specific aspects of their themes at congresses and seminars. Another important strategy has been to find qualified venues for the publication of selected contributions. This special issue is welcomed by the GTG Thematic Group on Quantum Physics Teaching / Learning as a further opportunity for growth in this field. We take the opportunity to present the GIREP Community on Teaching and Learning Quantum Physics, describing its origins, activities, and results as well as contributions chosen from among the best on the topic of quantum physics teaching / learning presented at the Leiden Congress 2025.

The **GIREP Community on Teaching / Learning Quantum Physics in Secondary School** was established in response to the increasing inclusion of 20th-century physics in national curricula across Europe which created a need for a coherent, research-based educational framework. While modern physics topics such as quantum physics have been included in secondary textbooks for over a decade, they were often presented in a fragmented or purely narrative way, lacking a solid theoretical foundation for students. Researchers, active in Physics Education Research (PER), have highlighted a strong need for organized curricula and educational paths to develop specific learning outcomes in this area and conceived the plan of founding a related community.

The community was formally initiated in **January 2019** through a letter inviting GIREP members interested in modern physics education to join a dedicated network. The primary goal was to identify researchers and practitioners worldwide who were willing to discuss and work on the topic of quantum physics education. This initiative aimed to recover, update, and improve upon the longstanding tradition of modern physics within GIREP, documented in numerous books and conferences since the 1970s.

The inaugural meeting took place during a symposium at the **Budapest 2019 Conference**. The response was significant: **46 applicants from 21 countries** (including 39 from the EU, four from the USA, and others from Malaysia and Vietnam) applied to join. The membership was diverse, primarily consisting of university faculty from physics and education departments, as well as secondary school teachers and researchers from national institutes. This group identified three main macro-categories for their initial work: **General Aspects** (vision and curriculum impact), **Contents** (topics and strategies), and **Teacher Education**.

The activities of the GIREP Community—now often referred to as the **GIREP Thematic Group on Teaching and Learning Quantum Physics (GTG TLQP)**—are centered on bridging the gap between research and classroom practice.

- **Discussion Workshops (DW):** The community organizes intensive workshops during major international conferences, such as those in Budapest (2019), Malta (2020, 2021), and the World Conference on Physics Education (WCPE 2024). These workshops are designed to reach a consensus on fundamental educational objectives and to produce scientific position papers reflecting the ongoing discussions.
- **Focused Thematic Research:** Recent activities have focused on high-priority topics such as **Quantum Entanglement**. For instance, in 2023 and 2024, the group organized workshops specifically to clarify how entanglement—a key concept for quantum technologies—can be effectively taught at different proficiency levels (awareness, understanding, application).

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- **Teacher Professional Development:** A significant portion of the community's work involves shaping teacher education programs. These initiatives emphasize the **"experiential model,"** where teachers go through the same learning paths as their students, using inquiry-based methods and digital tools like simulations.
- **Collaborative Scientific Production:** The community produces books of selected papers and specialized reports that analyze the effectiveness of different instructional approaches, such as the two-state system, wave functions, or Feynman path integrals.

Through these activities the GIREP Community has achieved several milestones that have influenced how quantum physics is taught in European secondary education. Among them are:

Scientific Position Papers: The group has drafted several position papers that serve as guidelines for curriculum designers and educators. These documents advocate for **"Quantum Literacy,"** emphasizing that conceptual understanding is central and that students should build a coherent picture of the physical world that includes both classical and quantum perspectives.

Identification of Core Concepts: Through its workshops, the community has identified a set of central topics that are considered essential for any introductory quantum course. These include **probability, duality / measurement / collapse, superposition, the uncertainty principle**, and **wave-like representations**. The group also recommends that teachers focus on the **conceptual role of mathematics**, using tools such as Dirac notation even at the secondary level, as these provide a clearer insight into the theory's workings than purely qualitative descriptions.

Synthesis of Teaching Approaches: The community has analyzed and compared various instructional paths, highlighting their specific strengths:

- **Two-state systems:** Best for introducing core concepts like qubits, cryptography, and computing.
- **Wave function approach:** Uses classical intuition about waves to build understanding of probability and the double-slit experiment.
- **Feynman path integrals:** Offers a conceptual way to calculate probabilities and treat duality.
- **Quantum Field Theory (QFT):** Provides a modern, relativistic view that resolves paradoxes related to the wave-particle duality.

Framework for Teacher Education: The community developed a robust framework for developing the **Pedagogical Content Knowledge (PCK)** of teachers. Key results include raising teachers' awareness of the **Nature of Science (NoS)**—helping them to address the historical struggle for interpretation—and ensuring they are capable of handling the cognitive conflict students face when moving from classical to quantum ideas.

Final Recommendations: A significant outcome is the ongoing effort to define **"minimal standards"** for quantum awareness. The community recommends a research-based style of cooperation where researchers and teachers work together to create modular, flexible materials that can be adapted to different classroom environments.

In line with these accomplishments, the papers selected in Leiden GIREP-EPEC Congress evidenced that the teaching and learning of quantum physics (QP) at the dawn of the **second quantum revolution** still presents a multifaceted challenge that spans across educational levels, from primary schools to advanced university courses. The following analysis illustrates the core problems addressed, the methodologies employed, and the primary results emerging from the provided sources treated in the submitted papers.

As the transition from classical to quantum physics involves a radical shift in ***Weltanschauung***, through undermining the deterministic paradigm of classical physics in favor of uncertainty, indeterminacy and non-locality, several specific hurdles for learning show up:

- **Conceptual and Mathematical Difficulties:** Learners frequently struggle with the **abstract nature** of quantum concepts such as superposition, entanglement, and the uncertainty principle. At the university level, students often conflate mathematical descriptions with physical meaning and struggle with complex formalism, such as Dirac notation and Hilbert space.
- **The "Historical" Misconception:** Research indicates significant gaps in historical and conceptual awareness. A survey of over 500 participants showed that only 5% correctly identified 1925 as the birth year of QM, frequently confusing it with earlier, incomplete models like Bohr's atom.
- **Teacher Preparation and Self-Efficacy:** Many in-service teachers have not encountered modern quantum technology during their own training and feel inadequate when explaining quantum phenomena or mathematical formalism. In primary education, this lack of knowledge often leads to **low self-efficacy** and a reluctance to teach Science and Technology (S&T).
- **Economic and Practical Barriers:** Experimental setups for quantum optics (like interferometers) are often too expensive and fragile for standard school budgets, forcing educators to rely solely on simulations.
- **The Pragmatic "Shut Up and Calculate" Attitude:** Standard university education often prioritizes computational proficiency over

conceptual and philosophical understanding, leaving students unable to explain what the theory actually *means*.

To address these issues, the papers presented in this issue propose and test several innovative methodologies:

- **Representation-Independent Formalism:** It is argued that teaching should start with **abstract operators and state vectors** (kets) rather than position-space wavefunctions. This avoids the confusion that arises when students conflate the "derivative" matrix representation with the abstract momentum operator.
- **Historical and Philosophical Integration:** Using history not as "background" but as a **structured learning tool** helps to clarify the Nature of Science (NOS). By analyzing the non-linear evolution from Planck to Heisenberg, students see science as a dynamic human endeavor rather than a set of final truths.
- **Haptic and "Low-Tech" Demonstrators:**
  - **Quantum Dice and Cards:** These tools use visual analogies to introduce axioms like superposition and measurement collapse without needing complex math. **Quantum Cards** specifically illustrate non-commuting observables (like color and figure) through a tangible, flipping mechanism.
  - **Pepper's Ghost:** This integrated Arts & Craft project introduces primary pre-service teachers to beam splitters, acting as a "conceptual anchor" for later quantum reasoning.
- **Low-Cost 3D-Printed Modular Kits:** The development of a **€200 modular system** allows students to build their own Michelson and Mach-Zehnder interferometers. This supports hands-on experimentation and provides classical analogues for concepts like the "quantum eraser."
- **Blended Learning for Teachers:** Training programs now combine **online self-study** (using interactive H5P elements) with synchronous online sessions and face-to-face workshops. This structure respects the heterogeneous backgrounds of in-service teachers.
- **The Quantum Field Theory (QFT) Framework:** Some argue that many conceptual hurdles in QM, such as wave-particle duality, are more easily resolved by moving toward a **field-based ontology**. Viewing particles as excitations of field modes helps students intuitively grasp why identical particles follow specific statistics.

The research conducted across these diverse settings yielded several key results:

- **Improved Conceptual Clarity through History:** Participants who studied physics concepts alongside their historical development showed a **better understanding** of the tentative and durable nature of scientific models. Control group comparisons showed that the experimental group had significantly higher awareness of the NOS (85-91% vs. 37-38%).
- **Effectiveness of "Representation-Independent" Approaches:** Using operators (like in the simple harmonic oscillator) is often seen by students as more **elegant and simpler** than solving intimidating second-order differential equations.
- **High Engagement with Haptic Tools:** In informal exhibition settings, activities involving direct manipulation (like the Quantum Dice and polarization filters) achieved the **highest scores** for understanding and engagement. Visitors reported that the exhibition was easier to follow than expected, suggesting that low-tech materials can bridge the gap to complex truths.
- **Attitudinal Shifts in Primary Education:** Pre-service teachers participating in the Pepper's Ghost activity began to view Science and Technology as a **creative, hands-on process** rather than a purely theoretical subject.
- **Democratization of Laboratory Skills:** The 3D-printed kits demonstrated that students can successfully adjust interferometers and obtain **real experimental results** within a single 90-minute lesson, proving that cost-effective hands-on learning is feasible.
- **Need for a "Copernicus" in Didactics:** There is a strong consensus that current curricula remain fragmented, with students able to solve formulas but losing the **logical connective tissue** between experiment, history, and formalism.

The collective evidence from these papers suggests that the future of quantum education needs to integrate historical context, precise language, and tangible, low-cost experimental tools, as all of them have a place in aiding students' learning. By shifting away from a purely "technical" image of physics and towards a more **reflective, cultural, and interdisciplinary dialogue**, educators can better prepare the next generation for the complexities of the quantum era.