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# Dialogue on current teaching practice and research-based proposals for quantum physics education

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**Abstract**
Quantum information science and technology has become a research field in physics education in recent years. The purpose of this paper is to provide an overview of the approaches used and experiences in teaching quantum physics (QP). A short questionnaire with 8 questions was distributed within the GIREP community. 92 respondents were counted as 51 filled questionnaires that could be analyzed. The results show that some strategies are specific for some educational levels, others are used throughout. The instructors are concerned by learning difficulties and perceive own difficulties in explaining quantum phenomena. Questions raised by respondents cover as well basic concerns as the practical realization of a QP course.

**Keywords:** quantum physics education, teaching/learning

## INTRODUCTION

We are amid the second quantum revolution. This quantum information revolution reveals great potential of the quantum framework for applications in quantum computing, communication, and sensing. It has simultaneously created urgency for preparing students to be leaders in these emerging areas. Educators and education researchers are investigating effective approaches to introduce quantum concepts in high school and university (Davis et al., 2025; Michelini & Stefanel, 2021, 2023), also developing interdisciplinary courses and curricula for students majoring in computer science, engineering, chemistry, mathematics, and other disciplines. These efforts aim to introduce students to foundational and advanced concepts in quantum information science and technology (QIST). To this end a great number of approaches are tested or thoroughly evaluated. So, in view of the international year of quantum science and technology, it seems it is time that the community of quantum physics (QP) educators exchange their experiences and learn from each other. Therefore the GIREP Thematic Group (GTG) on teaching and learning QP (Michelini et al., 2021) gathered information among the community on their experiences in teaching QP and collected questions concerning different aspects of teaching and open research topics in quantum education. While the European education community has long been deeply engaged in introducing quantum concepts early in K-12 curricula, other countries including the United States have only recently recognized the value of engaging K-12 students with potential of QIST (e.g., https://q12education.org/). Many countries have QP in their curricula in high school (Stadermann et al., 2019). The taught content and approaches vary widely depending on the goals (Michelini & Stefanel, 2023), also in teacher education (Michelini et al., 2022b). The traditional approaches often emphasize the wave-particle duality. But in QIST the use of two-state systems is recommended. These address the fundamental concepts of QP, even if they may not cover multiple-state or infinite-state systems. More ambitious approaches using quantum field theory or Feynman's path integrals have been proposed. At post-secondary

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**Contribution to the literature**

- This paper describes an overview over current teaching practices in quantum physics on different educational levels inside the GIREP community.
- It also addresses challenges encountered by quantum educators and provides answers based on existing empirical evidence.
- In answering specific questions from the community it gives recommendations for choosing content and shaping quantum physics teaching on different levels.

**Table 1.** Overview of the structure of the questionnaire

| Item | Answer format | Number of answer options |
|---|---|---|
| How many years of experience do you have | Closed/comment possible | 4 |
| Focus of teaching | Number (percentage) | 4 |
| Existing curriculum | Closed | 3 |
| Which approach do you teach? | Closed/comment possible | 7 |
| Which kind of formalization, if any, is chosen? | Closed/comment possible | 7 |
| Which methods are used? | Closed/comment possible | 7 |
| Which media are used? | Closed/comment possible | 7 |
| Observed learning difficulties | Open | |

level a number of courses specifically aiming at educating quantum engineers have been created and tested in accordance with the goals of the European quantum flagship project. At general-public level, but useful also in education, a number of quantum games have been developed to create a kind of experience with the quantum world (Montagnani et al., 2023). However, research data on these different approaches is still scattered and mostly fragmented. Therefore a review of the approaches used and experiences with them seems helpful for the community of quantum instructors.

## RESEARCH DESIGN AND METHODOLOGY

### Research Questions

According to the rationale, the following research questions have been formulated:

- Which strategies and elements characterize the teaching practice in QP today?
- In which way do instructors use strategies at different educational levels?
- On which teaching aspects there exist open questions among instructors?

### Methodology

To answer these questions a short questionnaire with 8 questions was set up by the GTG-leaders (https://www.girep.org/thematic-groups/teaching-and-learning-quantum-physics/) in several discussion rounds (see **Table 1**). The goal was to identify the participants' experience with teaching QP, the focus of their teaching, approaches used, kind of formalization, methods and media. In particular, the questions were posed in a way allowing for open answers or remarks in order that the respondents` answers are not biased. There were 8 questions, 7 of them with closed answer format, partly allowing for open ended comments. 1 item had an open-ended answer format explicitly asking for observed learning difficulties. The answers to the open item were summarized and then grouped according to inductively derived categories describing the perceived learning difficulties.

In addition the questionnaire contained one extra item: "I have the following questions: …" This item explicitly mentioned the following 6 aspects to which the respondents could formulate their questions or concerns. During the symposium, these were answered in short presentations by five expert quantum educator-researchers:

1. Teaching the basic principles of QP
2. Role of formalism in teaching QP
3. Role of representations and visualizations
4. Strategies to enhance learners' involvement
5. Connection of quantum technology and fundamental QP
6. Teaching controversial topics, e.g., with respect to interpretation

## FINDINGS

### Description of Participants

The target group were all GIREP members who were invited by email to participate. The questionnaire was then sent in advance to all registered participants of the GIREP-EPEC 2025 conference. There were 92 submitted questionnaires of which 30 have been completed with all items and partly commented. 21 questionnaires were only partly filled with no comments. The other questionnaires did not contain any answers; partly

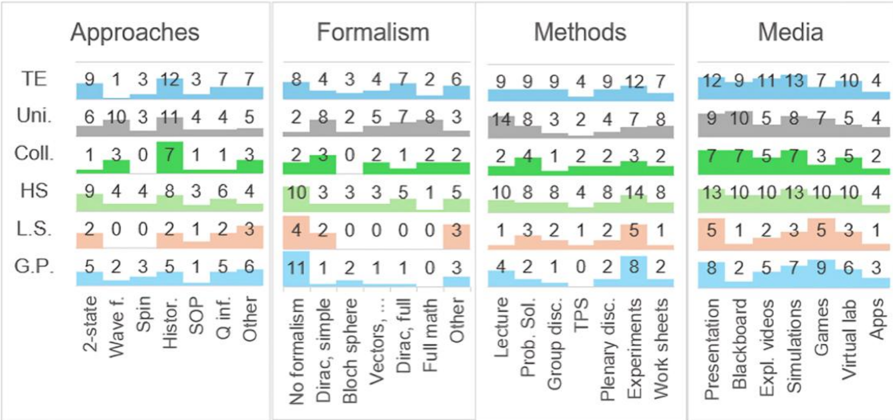


**Figure 1.** Overview of the usage of different aspects in quantum teaching (the educational levels are: G.P.: general public, L.S.: lower secondary school, HS: high school, Coll.: college, Uni.: university; TE: teacher education; the characteristic focus in each aspect can be observed, especially with respect to the choice of approach or the use of formalism; in the horizontal axis are depicted: approaches [2-state, wave function, spin (Bitzenbauer et al., 2024), historical examples, sum over path, quantum information, or other], formalism [no formalism, Dirac notation, bloch sphere, vector description, full Dirac formalism, full mathematics, other], methods [lecture, problem-solving, group discussion, think-pair-share, plenary discussion, experiments, work sheets], media [presentation, blackboard videos, simulations, games, virtual lab, apps] (the authors' own graph)

obviously the questionnaire was opened online but has not been worked upon. In the analysis the 51 questionnaires with answers were considered. The extra item concerning questions was answered overall by 12 respondents, each one formulating questions for one or several of the named specific aspects.

Of the respondents, 47 gave information on their experience. 6 of them reported that they did not teach QP. 14 teach QP for one of the possible levels, 3 on all of the indicated levels, possibly with different duration of their teaching experience. Most respondents had experience with less than 5 years for the respective levels, but some more than 20 years. Many respondents teach on several levels, e.g., university and general public or in high school and teacher education. So we can state that the respondents are distributed on a broad range of experience. Concerning the curriculum, participants mostly have some flexibility or even can create their own curriculum.

## Quantitative Results

The participants gave information on the approaches, the level of formalism, methods or media used during their teaching (see **Figure 1**).

In the approaches, it is observed that sum over path or spin are only taught seldom. Mostly 2 state systems and/or a historical approach are chosen. Wave function is used mainly at university. Quantum information as approach is more often named in teacher education, school, and general public than in university or college courses. For the general public or school in general no formalism is used, and full math is found mostly at university. In the answers we observe a big variety of methods and media used. At university, lectures are dominating whereas at school or for general public experiments are in the foreground. Cooperative methods are mainly used in school or teacher education. As concerns media, presentations are used on every educational level, blackboard mostly at university or college, games mostly for the general public or school. Apps are not used so often.

Overall, the impression gained was that teaching, particularly at colleges and universities, is still heavily influenced by traditional teaching content in quantum theory rather than by the latest developments in quantum information.

## Perceived Learning Difficulties

In item 8 of the questionnaire, the respondents named learning difficulties in the corresponding open-ended item. Some described learning difficulties could be perceived as "teaching" difficulties. The answers have been summarized, separately for the main educational levels:

- General public: On this level the difficulties in explaining QP are discussed, highlighting the aim to generate interest in the subject without focusing on complex math. Challenges include dealing with abstract concepts and explaining interpretations. There is a need to simplify explanations accurately to avoid misconceptions and retain audience engagement.
- Secondary school: The perceived difficulties range from conceptual hurdles like understanding superposition, wave-particle duality, and the uncertainty principle to practical issues such as connecting abstract theory with experiments. Educators also struggle with finding suitable activities, addressing students' unfamiliarity with

core concepts like waves and probability, and explaining the interpretation of quantum mechanics (QM), including measurement and the collapse of states. Furthermore, students find it challenging to grasp abstract ideas like state vectors in complex space and the concept of spin, highlighting the need for improved pedagogical approaches and appropriate visualization.

- College and university: Instructors report significant difficulties in teaching QM, primarily due to students' challenges with the complex mathematical formalism required and their struggle to develop an intuitive understanding of abstract quantum concepts. Educators also note that traditional curricula are often too packed for one semester, limiting time for in-depth discussion and exploration of physics beyond problem-solving techniques. Furthermore, students lack the necessary math skills and often confuse mathematical descriptions with physical meaning, hindering their ability to visualize and analyze quantum systems effectively. The difference between physical space and abstract state space and understanding concepts like superposition also pose significant hurdles.
- Teacher education: The answers address the significant hurdles encountered when introducing QP, among them the teachers' lack of adequate preparation. The inherent complexity of quantum concepts like wave-particle duality and superposition poses difficulties for both educators and students. Finally, it touches on the challenges students face with abstract mathematical representations, such as understanding state vectors and wavefunctions.

Additionally to this verbal summary, the following categories of learning difficulties regarding the content were identified: "*understanding concepts*" (14 coding), an exemplary quote being: *"interpreting superpositions,"* "*mathematical structures*" (6 coding) with the quote: *"difficulty in understanding the difference between a vector in our physical space and in a state space especially"* and "*difference of classical and quantum physics*" (3 coding). Regarding the views of students we identified: "*interest of students*" (7 coding) or "*missing skills or previous knowledge*" (11 coding). As a teaching difficulty the category "*explanation difficult*" (4 coding) was found, highlighted by the quote: *"the struggle is to find a convincing way to explain interpretations of QM."*

## ANSWERS TO EXTRA ITEM: ADDRESSING THE QUESTIONS OF THE PARTICIPANTS

The respondents formulated questions related to the given aspects. The answers to these questions are presented in the following, separately for the perspective of teaching QP at school, and teaching QP at college or university. The questions also show that there is a strong need for relating the foundations of QP to the new quantum technologies, especially quantum information. The answers given below reflect the views and experiences of the authors.

### Quantum Education in School

One of the most frequent questions posed by the community of GIREP colleagues is related to the question of when and how it is possible to "teach the basic principles of QP."

#### *Question group 1: When and how to teach the basic principles of QP?*

There is a wide debate in the literature and review works are now also available (Michelini & Stefanel, 2021, 2023). A community has been operating in GIREP since 2020 (Michelini et al., 2021), which has produced contributions on teaching/learning QP every year. From a research perspective, there is a very recent special issue of the Physical Review-Physics Education Research (Davis et al., 2025). The different possible formulations and interpretations of QP have been adopted as perspectives/approaches for different teaching/learning proposals:

- A rational reconstruction of the historical development of ideas, starting from light emission problem and blackbody study.
- The interpretation of crucial experiments and the birth of quanta interpretations (photoelectric, Compton, Zeeman effects), from historical point of view.
- The wave formulation.
- The vector formulation proposed by Dirac.

Approach 1 and approach 2 emphasize the transition from continuous to discrete in the representation of physical quantities; it is fascinating and motivating in the rational reconstruction of ideas. It can be addressed by means of a historical analysis of unsolved problems and/or results of experiments from the classical point of view, but it is based on a phenomenological treatment of some aspects and it remains on a descriptive and semi-quantitative level, documenting the acceptability of individual assumptions. The main purpose is to raise awareness of how scientific knowledge was developed in the interpretative revolution that led to QM. We hope this will become part of the culture of all citizens, but we wouldn't want the unifying dimension of QM's theoretical thought to be lost. On an educational level, we have to offer at least the founding elements of the new theory in a coherent conceptual framework. QM is in fact the theoretical foundation presenting a culturally new approach of physics phenomena interpretation (Ghirardi, 2005).

For this reason, approaches to the appropriation of the basic concepts of the theory have been proposed in contexts that can be interpreted with a two-dimensional vector space (Davis et al., 2025; Michelini & Stefanel, 2021, 2023) and there is already evidence of effectiveness, for example, with regard to measurement (Bitzenbauer et al., 2024; Toth et al., 2025). One of the first proposals of this type is based on optical polarization and is still the subject of several implementations (Davis et al., 2025; Michelini et al., 2022b). It consists of the first steps towards an interpretation consistent with the basic formalism: an introduction to the ideas of theory. The main learning goals are

- Preparation and quantum measurement, focusing on its stochastic nature
- Mutual exclusive and incompatible properties, and uncertainty principle
- State as a vector: containing all possible measurement outcomes
- Superposition principle
- Prediction of a measurement and probability
- Entanglement
- Non-locality

The main features are, to

1. explore the polarization of light from an experimental, conceptual and formal point of view,
2. discuss simple ideal experiments of interaction of single photons with polaroid and birefringent crystals (calcite crystals), and
3. describe in quantum terms in a two-dimensional vector space the polarization state of light.

The designed path (Davis et al., 2025) has been completed with formalism and implemented in 85 schools of 5 countries (Michelini & Stefanel, 2023; Michelini et al., 2022b) and more recently with the reinforcement of quantum games (Montagnani et al., 2023). It is suitable also for introduction of quantum information technologies as described below.

### *Question group 2: The use of formalism in teaching QP*

The approach, described above, uses an ordinary 2-dimensional vector space, because it is familiar to students and does not introduce an additional cognitive load with respect to ket and bra formalism. Starting from a classical interpretation of polarization, the quantum state is assumed to be a vector. The exemplary case of 45° polarized photons is discussed to distinguish "property" from "state" and to exclude a statistical mixture. Its state is $(u+v)$, $u$ and $v$ being the base of the two dimensional system. From Malus law, it is known that the transmission probability $P_t$ for $N_t$ transmitted photons from $N$ incident photons, when $q$ is the angle between the two permitted directions of polaroid is $P_t = N_t/N = \cos^2 q$. The transition probability from state $u$ to state $w$ can then be written by the scalar product of the two vectors $P_t = \cos^2 q = (u \cdot w)^2$ . This basic trigonometric relation is the basis of the unitary nature of quantum states. Another important issue addressed is the role of representations and visualizations.

### *Question group 3: The use of representations and visualizations*

To foster the distinction between state and property and the awareness that they live in different spaces, in the described path an iconographic language is used (Michelini et al., 2016).

### *Question group 4: The involvement of learners: which strategies are possible?*

Learning requires the personal involvement of the subject in the object of study: the appropriation of concepts requires experience them. In the path based on polarization in QP, the student:

1. personally conducts simple experiments with polaroid and birefringent crystals,
2. is addressed by tutorials stimulus issues to build interpretative reasoning, and
3. experiences the role of a theoretical physicist by designing and reviewing the outcomes of ideal experiments with an open simulation environment.

Offering the learner the opportunity to experience the way of working as a theoretical physicist by means of ideal experiments is the way to allow each student to build their own personal appropriation of concepts. JQM software is an open environment in which students plan ideal experiments and explore the outcomes of interactions of beams and single photons, polarized according to a chosen direction or non-polarized, with single or sequences of polaroid in a different allowed direction and/or with birefringent crystals oriented according to chosen directions (Michelini et al., 2016).

To complete these aspects, see also framework section. Furthermore, it seems appropriate to point out the position papers produced by the GTG on teaching/learning QP, especially on teacher education and the available resources (Faletič et al., 2024; Michelini et al., 2022a, 2023).

### *Question group 5: Why teach quantum technologies?*

Teaching quantum technologies among them quantum information might serve different goals: motivating students and educating them as future citizens. For this the students should be provided with the competence to understand or judge media reports, YouTube videos, blogs, or similar texts on quantum technologies in order to be able to distinguish fake news, serious repost or exaggerations. This skill requires at least a basic understanding of the quantum concepts (see question groups 1-3) , mainly super position and entanglement and how these principles are used, e.g., in quantum technologies (Pospiech, 2021). As the way these concepts work in quantum technologies generally is not straightforward, it is necessary to teach a carefully chosen quantum technology (e.g., quantum cryptography) explicitly and in an exemplary way. By getting insight into quantum technologies students see the relevance of QP beyond the theoretical description, thus bridging the theory-practice gap. At the same time they perceive that physics in general and especially QP is a topic of actual research with impact on everyday life. This might also contribute to demystifying QP and promote a pragmatic stance. Of course, all these teaching objectives require a great deal of insights from the side of educators and teachers. As a rule these have not (yet) received an introduction to quantum technologies, so that they grapple with their own need for understanding them and the current status of their development. Therefore, there is a need for explicit integration of quantum technologies into the curriculum for teacher education (Förster & Pospiech, 2025). First experiences with integrating quantum technology into lessons show promising results (Förster & Pospiech, 2025; Kelly et al., 2024). In order to support teachers, many resources are available, as seen, e.g., on https://qtedu.eu/material-and-tools/primary-and-secondary-school and the links therein. Specifically for quantum computing the site: https://quantum.cloud.ibm.com/ is a good point to start. Concerning the question if early exposure aids or hinders understanding of quantum concepts, there is no reliable evidence.

**Teaching approaches and possible content:** The range of possible applications is very broad. There are attractive fields such as quantum sensing using NV centers which might be used in, e.g., medical applications (EEG, cancer monitoring, etc.). Also in quantum cryptography commercial solutions are already available. Quantum computing is attracting great attention even if it still is a vision but research is making rapid progress envisioning applications in areas like logistics, traffic regulation, and so on. Most of these applications can be taught if a suitable approach is chosen. This will be a spin-first approach directly leading to an understanding of Q-bits or the states of NV centers. Teaching quantum concepts and quantum cryptography or quantum computing can be interlaced (Pospiech, 2021). On the whole one could wish for the integration of new quantum technologies into the physics curriculum both at school and in teacher education at university.

### *Question group 6: Controversial issues – Interpretations of QP*

The questions circle around the possibility of teaching a controversial topic in school (Justice et al., 2025), referring to the longstanding, still not finalized, debate on interpretation of QP. Teaching this debate has to pinpoint the core of the interpretational problem, namely different conceptual approaches to the measuring process:

- There is no measurement problem (e.g., Bohmian mechanics)
- There is no measurement (e.g., many world interpretation)
- Measurement is decided by the observer (e.g., Q-bism)
- Measurement is a separate process outside QP (e.g., v. Neumann-collapse)
- There is continuous measurement (e.g., decoherence theory)

For further hints to teach these topics with respect to the nature of physics (see Stadermann & Goedhart, 2021).

## A Framework to Help Answer Open Questions

In teaching, like in research, teachers usually subscribe to a set of paradigms or frameworks, lenses through which they view learning and according to which they plan their teaching. Many of the questions asked by the respondents will be answered in different ways given different frameworks. The framework described in this section is based on four fundamental considerations:

1. Students learn by engaging in the learning cycle (Kolb, 1984). Two out of four parts of the cycle are:
   (a) creating ideas about how things work (abstract conceptualization) and
   (b) testing them (active experimentation).
   We cannot create ideas for them, we can only help them create good ideas through testing.
2. The goals of instruction must be concrete. What will the students be able to do? This helps to stay on track and not wander astray in the beautiful landscape.
3. People remember stories. Any lesson can be set up as a story following a narrative arc, starting with a question, and ending with the answer. The lesson(s) are about learning the concepts that are needed to answer the question (rising action and climax). In the falling action, the students should be able to answer the initial question by themselves.
4. Students should always ask: how do we know this? Where does this knowledge come from. In science, it is mainly from experiments. When classical models fail to make predictions that conform to reality there is a necessity for new models. We accept them, if they work, and keep

testing them. This is the fundamental nature of science and a worthy goal to address on its own.

We will address respondents' questions in light of these four fundamental considerations.

#### *Where should we start and how deep should we go?*

One set of questions from the respondents asked about topics to cover. There is really no one answer to such questions, but there are general guidelines: think of the story and the goals. Students should be presented with questions that they will be able to answer after instruction. If algorithms are the goal, then basic QP may be unnecessary. It suffices that the students learn the gates and what goal they need to achieve. If an explanation of a new phenomenon is the goal, then fundamental, generally applicable concepts must be covered. One might be tempted to just postulate the rules of QP, and some students would learn them as if it was a game, like chess or poker. But if we want students to be able to answer the question "How do we know?" then we need to address how made-up ideas become accepted models in science. Whether we want to present them as fundamental rules, rather than derived ones, depends on how we know about them. If they were proposed directly from observations, and cannot be derived from more basic rules, then, for now, they are fundamental.

#### *How much formalism should we include and how many interpretations?*

QP is written in the language of mathematics. There are multiple interpretations. How do we know which is better? Until we can distinguish between them using the scientific process they are all equivalent. Any interpretation that a student creates in their mind might be better than any already existing one, as long as it is mathematically represented in a way consistent with QP. This shows us that formalism plays a conceptual role in QP. We cannot properly teach or reason conceptually about QP, unless the concepts that we teach can be uniquely mapped to the standard mathematical representation.

But mathematics is just one possible representation. There have been proposals (Emigh et al., 2020) to represent probability amplitudes in different ways: by the direction of a raised hand, by an arrow (phasor). There are also many phenomena where knowledge of probability distribution suffices. How appropriate it is to include mathematical formalism as a representation depends also on the effect such inclusion will have on the story. Will students be able to better answer the questions or will it be just a confounding factor. If mathematical concepts are necessary, but cannot be productively included in the story, then the goals must be adjusted accordingly.

Experience shows that Dirac notation or an equivalent mathematical notation are entirely appropriate for secondary school students. In any case, thinking about how mathematics can help or hinder the story can be useful in making the decision.

#### *But the students' attention span ...*

We are all living in an ever accelerating world, where *tl;dr* ("too long; didn't read") seems to be a real concern. However, students still go to the movies, (or watch movies otherwise), so they are clearly capable of holding attention to stories that they find interesting. So let us structure lessons as stories. Let us engage the students in discovery. But stick to the goal to avoid overload and use such representations that can support students in their reasoning. However, students should be aware that with limited reasoning resources they can only solve a limited set of problems. And whenever in doubt, ask: "how do we know this?" If the answer is that we do not, then we should not pretend that we do. Why is QP such as it is? We do not (yet) know.

### Quantum Education in College or University

In this section the questions are answered from the perspective of higher education.

#### *The challenge of quantum formalism*

Quantum formalism is inherently abstract and non-intuitive. The quantum state of a system is described by a state vector, and the Hamiltonian governs the system's time evolution. Even students who have mastered classical concepts struggle with quantum formalism. For example, while position and momentum evolve deterministically in classical physics, in QP they are operators acting on states in Hilbert space, and measurement collapses the quantum state into an eigenstate of the operator corresponding to the physical observable measured.

Helping students at all levels learn quantum formalism that builds appropriately on their prior knowledge and skills is paramount. For interdisciplinary students interested primarily in QIST, knowledge of two-state systems and their product space is sufficient. However, normalizing the language of QM to make it appropriate for students from interdisciplinary backgrounds requires careful consideration.

#### *Balancing abstraction and physical basis in QIST education*

Several linguistic simplifications have emerged: using "qubits" instead of specific two-state systems, "measuring a qubit" and "measurement basis" instead of measurement of physical observables yielding eigenvalues. Describing quantum time evolution in terms of quantum gates rather than the system's Hamiltonian has made QIST education less physicscentered, reducing cognitive overload for non-physics students and preventing QIST courses from being perceived as QP courses. However, without systematic research and development regarding a framework for QIST education, the appropriate balance between abstraction and physical basis for interdisciplinary courses at different levels remains unclear. This balance is particularly important at this early stage of the second quantum revolution, when different qubit architectures (superconducting, neutral atom, ion trap, semiconducting, etc.) are competing to develop fault-tolerant scalable quantum computers. This contrasts with classical computers, where semiconducting technologies are mature and the quantum mechanical nature of transistors can be abstracted away.

### *Multiple representations and learning tools*

Effective use of multiple representations can support interdisciplinary students in learning quantum concepts, as the ability to translate between different representations is a hallmark of expertise (Marshman et al., 2024). Visualization tools, including interactive simulations, can greatly aid student learning. Low-cost hands-on tools also offer pedagogical value. For example, we are developing tutorials involving Bloch cubes to engage students at different levels with quantum concepts including quantum gates, measurement, and entanglement (https://www.blochcubes.org/). Similarly, students engaging with three low-cost polarizers and a beam of light can learn about quantum measurement using analogical reasoning between a beam of light and single photons (Pospiech, 2021).

Education research should focus on appropriate ways to introduce mathematical representations in quantum and QIST curricula (Seiffolahi & Singh, 2025), considering students' level of expertise and familiarity. This enables students to integrate quantitative and conceptual aspects to organize, extend, and repair their knowledge while avoiding cognitive overload. As students develop proficiency, they require less scaffolding support and can effectively use different representations in problem-solving.

### *Research-based development and assessment*

Developing research-based curricula and pedagogies requires investigating students' prior knowledge and skills while staying within students' zone of proximal development. This development and assessment is an iterative process involving both qualitative and quantitative research methods (Doyle et al., 2026; Justice et al., 2025). Qualitative approaches such as individual think-aloud interviews and focus group discussions provide in-depth understanding of what students have learned and can demonstrate in various assessment tasks, both after traditional lecture-based instruction and after evidence-based active engagement curricula involving teaching-learning sequences, think-pair-share exercises, and hands-on learning activities. Quantitative assessment tools, including pre- and post-tests administered before and after learning with research-based quantum tools, can evaluate the effectiveness of learning interventions. Quantum assessment at all levels should also focus on student attitudes, interest, engagement, and other social-psychological measures before and after engaging with research-based learning tools.

## DISCUSSION AND CONCLUSION

Teaching QP—particularly entanglement and quantum information science—requires innovative, research-informed approaches that bridge theory and real-world relevance. This study highlights with the example of the GIREP community the diversity of used strategies across all educational levels which partly is still influenced by traditional approaches. The observed learning difficulties hint also to the inherent difficulties of finding appropriate explanations for the respective target group. In higher levels the formalism and mathematical skills of learners remains a central concern of educators. The questions asked by the respondents cover the entire range of teaching aspects and are discussed from school perspective and college perspective with hinting to research desiderata. Moving forward, evidence-based teaching, teacher training, and activating pedagogy are essential to equip learners with the knowledge and critical thinking skills needed for the quantum era.

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