Teaching and learning quantum entanglement

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Abstract. At the GIREP 2023 conference, the GIREP thematic group "Teaching and learning in quantum physics" has organised a discussion workshop on quantum entanglement. Several findings emerged from the discussion, and several further questions were opened. In this discussion workshop we propose a series of focused questions that will expand on the topics discussed in 2023 and suggest teaching/learning ways. The organisers will invite interested participants to prepare their position on the questions and present them in the discussion. The goal of the discussion will be to provide a community-based position paper on the questions discussed.

Motivation

The discussion workshop organized by the GTG "Teaching and Learning Quantum Physics" (GTG TLQP) at the GIREP conference in 2023 sparked a lot of interest in the topic from the community. The purpose of the GTG is to bring together the community to discuss important topics. Given the interest in the 2023 discussion workshop, we decided to expand on the topic based on the contributions discussed in the 2023 workshop and the additional contribution coming from a call to all GIREP members.

We give the most important findings from 2023 here for reference [1].

First, conceptual aspects like the relationship between entanglement, non-locality and non-separability were discussed as well as perspectives like holism.

Second, three distinct perspectives on representation of entanglement have been identified. We provisionally labelled them representational paradigms. A *mathematical* view suggests that entanglement should be represented mathematically, a conceptual view suggest to focus on *linguistic* aspects able to express physics meaning, and the *pragmatic* perspective argues for a practical definition based on experiments and their outcomes or possible outcomes. The question arose whether it is possible to map descriptions used in one view to those used in the other views in a one-to-one manner.

Third, it was found that the elements of understanding entanglement depend a lot on the representational paradigm and the context of learning entanglement.

Fourth, in the post-workshop discussion, a request was forwarded to the GTG to describe the "minimal standards" of learning entanglement at various proficiency levels and various educational levels. As proficiency levels, reproduction-directed, meaning-directed and application-directed levels were proposed; as educational levels, primary school, secondary school, university and other, with outreach as an example of other, were proposed.

We find all these topics worthy of discussion and are proposing a discussion workshop to address them, enriched by examples of educational proposals.

Aims of the workshop

Given the open questions in the introduction, we propose the following topics for discussion:

1) How can we map between the different representational paradigms;
2) How to individuate minimal standards of learning, possibly in terms of each representational paradigm.

3) How to evaluate awareness, meaning and application for each context and school level (see table 1)
4) How to operationalize the concept of entanglement by means of evidence-based proposals.

Topic 1). We propose to identify the fundamental elements of learning in any of the representational paradigms and contexts.

Topic 2). Once the fundamental elements of learning are identified, the community can attempt to list a series of intended operational outcomes of learning at different proficiency and educational levels. We suggest a modified set of levels as seen in table 1.

Table 1. Table captions are in Times New Roman, size 10 and centred. Insert table below.

	Outreach	Primary school	Secondary school	University
Awareness-directed				
Meaning-directed				
Application-directed				

Topic 3) Find an agreement to fill-in Table 1

Topic 4) Evidence-based implemented proposals will support the previous goals.

Methods

The organisers will contact the GIREP community with an invitation to contribute to the topics described above. The organisers will make the contributions available to the participants in advance. The workshop will be comprised of short presentations that present views on the topics, followed by a 60-minutes discussion on the topics. The last 15 minutes will be reserved for summarising and confirming the level of consensus on the topics.

Outcome

The outcome of the discussion workshop will be a position paper detailing the findings of the workshop. Where consensus has been reached, evidence supporting such consensus will be referenced. Where consensus could not be reached, points of contention or lack of evidence will be reported to motivate further research.

The outcome of the workshop will provide an important stepping stone in the teaching of entanglement as it will be the product of discussion among experts in the field and based on available evidence. Ideally, it may even set standards of language use for the topic.

References

[1] S. Faletič, M. Michelini and G. Pospiech, Teaching and learning quantum entanglement (submitted to the GIREP 2023 conference proceedings)