frontiers | Frontiers in Quantum Science and Technology

TYPE Editorial
PUBLISHED 04 July 2024
DOI 10.3389/frqst.2024.1424698

OPEN ACCESS

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RECEIVED 28 April 2024
ACCEPTED 18 June 2024
PUBLISHED 04 July 2024

CITATION
Chiofalo ML, Smerzi A and Michelini M (2024), Editorial: Responsible research and innovation in quantum science and technologies. *Front. Quantum Sci. Technol.* 3:1424698. doi: 10.3389/frqst.2024.1424698

Editorial: Responsible research and innovation in quantum science and technologies

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KEYWORDS

quantum science, quantum technologies, physics education research, physics outreach research, outreach

Editorial on the Research Topic
Responsible research and innovation in quantum science and technologies

Quantum technologies (QTs), and the basic quantum science (QS) they build on, are at the centre of stage of science and humanities. Their potential–and to certain extent-their actual capability, lies in revolutionizing our daily lives, shaping our way of thinking also driven by the weirdness of quantum mechanics, developing human capacity, shaping community living, influencing ethics, moving in entirely different economy and job market.

Examples are in environmental-safe and sustainable development with the engineering of more efficient batteries; molecules engineering for pharmaceutic personalized medicine; intrinsically secure communications; ultrasensitive sensors with applications from health diagnostic to blind airplane navigation; optimization/solution of complex-networks problems like logistics, finance, artificial intelligence and even the brain. All hard sciences, philosophy, economy, as well as juridical, social, policy-making sciences are being affected while xillions of dollars are invested by public bodies and companies, and the six Responsible Research and Innovation (RRI) dimensions are crossed.

In this scenario of global movements with terrific proportions, the undeniable need emerges of uplift citizens culture and awareness and of preparing a suited workforce in the new ecosystem. The exciting opportunity is thus offered, for a massive education on elementary quantum science and more complex quantum technologies, in an RRI approach, where all the six dimensions are involved: gender, open access, science education, public engagement, governance and ethics.

However, educating a general public to QS is a formidable challenge, due to the existing limitations in the experimental, creativity, and mathematical literacies ordinarily required in scientific thinking, that in the case of QS and QTs become real hampers. Education and outreach in QS and QTs then risks to be a bare transmission of historical facts and scientific factoids using often misleading analogies, with no real understanding nor education to scientific thinking. The development of a research-based approach to outreach is required, which we might call Physics Outreach Research (POR).

While dedicated programs are being developed in Europe, like the QTEdu-Quantum Flagship, United States, China, Japan, India, a number of questions remain wide open, with

this Research Topic we aimed at addressing research questions such as: (**RQ1**) how to effectively engage learners and support teaching/learning environments in QS and QTs with rigorous use of scientific thinking processes; (**RQ2**) whether efforts in outreaching on QTs and on QS be mutually helpful; and (**RQ3**) whether Research efforts in Physics Outreach (POR) and Education (PER) as well be mutually benefitting from each other, that is whether they do share an intersecting ground of contents and methodologies.

The article by Ubben and Bitzenbauer "*Exploring the Relationship between Students' Conceptual Understanding and Model Thinking in Quantum Optics*" provides one answer to (**RQ1**). One of the most important teaching problems is the conceptual change of ideas from common to scientific sense: how much models based on the Gestalt construct help the acquisition of quantum mechanics concepts? The study, conducted with 116 secondary school students, explores the role of constructs Functional Fidelity (FF) and Fidelity of Gestalt (FG) in acquiring conceptual mastery in quantum optics, which has no representations related to experience. The strong correlation emerging between the photon-model understanding and elementary quantum-mechanics concepts within FF highlights the didactic importance of this kind of model reconstruction in quantum physics thinking. This outcome can inform instructional strategies for quantum physics education and outreach, thus relevant also to (**RQ3**).

The articles by Vaidman, "*Lying particles*" and by Bruno Julia Diaz, Francesc Sabater Garcia and Carles Caldero "*Eigengame: a primer to introduce wave functions and probabilities*" open a window on all three **(RQ1)-(RQ3)**. There, quite interesting examples are shared about innovative methods and tools that can keep in the scientific thinking process forms of experimental (the former) and mathematical (the latter) language in PER and POR activities. In fact, Vaidman addresses one key issue distinguishing quantum from classical thinking: non-locality, i.e., the impossibility of defining a trajectory to quantum objects. A definition is proposed, based on the idea that a pre- and post-selected particle can be in several, possibly disconnected, regions simultaneously. The work discusses the different theses in literature and advances them by moving from ideal to real experiments with Mac-Zender interferometers, completing a previous study by Danan (2013). Sabater et al. propose the software Eigengame with a visually appealing interface, a math-conceptual lab for a confined electron in one dimension. By playing the game, the user develops intuition on key quantum-mechanics concepts: wavefunction and how they are affected by confining potentials, eigenfunctions associated to energy levels, measuring process. As a tool, Eigengame helps grasping fundamental aspects of quantum mechanics. As a game, it fosters students' motivation.

Finally, the article by Greinert et al. "*Towards a Quantum Ready Workforce: the updated European Competence Framework for Quantum Technologies*" enriches this Research Topic with an overarching, indispensable, and updated conceptual map of the ongoing pioneering and valuable efforts produced within the European projects QTEdu and QUCATS. These have led to define the European Competence Framework for Quantum Technologies and its role in quantum technology education, that is central also to the European Quantum Readiness Center and source for a forthcoming European certification scheme to standardise industry training.

The Research Topic Editors are grateful to the Authors' for their consideration of the Research Topic timeliness, the importance of a RRI approach to Quantum Technologies being a relatively new subject. The Editors have also appreciated the Authors commitment in offering to the community high-quality articles with original angles on this very vivid field of PER and POR. We wish this Research Topic can motivate and inspire other scholars and colleagues to actively contribute to Responsible Research and Innovation for Quantum Science and Technology.

Author contributions

ML: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. AS: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing. MM: Conceptualization, Data curation, Formal Analysis, Funding acquisition, Investigation, Methodology, Project administration, Resources, Software, Supervision, Validation, Visualization, Writing–original draft, Writing–review and editing.

Funding

The author(s) declare that financial support was received for the research, authorship, and/or publication of this article. This project has received funding from the European Union's Digital Europe Programme DIGIQ under grant agreement no. 101084035, and from the National Centre on HPC, Big Data and Quantum Computing–SPOKE (Quantum Computing)—European Union Next-GenerationEU—National Recovery and Resilience Plan (NRRP)—MISSION 4 COMPONENT 2, INVESTMENT N. 1.4—CUP N. I53C22000690001, and from the projects PRA_2022_2023_98 "IMAGINATION" and MIT-UNIPI program.

Conflict of interest

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The author(s) declared that they were an editorial board member of Frontiers, at the time of submission. This had no impact on the peer review process and the final decision.

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