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Educating to the "Culture" of Quantum Technologies: A Survey Study on Concepts for Public Awareness

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ABSTRACT

In this article we offer a conceptual and practical contribution to the field of STEM education by investigating the concepts educators may include in Quantum Technologies (QT) outreach activities. We embed our approach in the discipline-culture (DC) framework, in which we consider the cultural nuances of QT as an important factor which must not be ignored in education efforts. To this end, a survey study by the pilot project Quantum Technologies Education For Everyone (QuTE4E), investigating key concepts for QT outreach, was conducted between December 2021 and June 2022. Here we present the results of the study, analysed through the DC framework, and consider the implications for designing QT outreach activities. The data hints at the perceived value of highlighting core concepts of Quantum Mechanics (QM), while also raising the question of whether QT sits as a discipline of Physics, Computer Science, or elsewhere. This calls for a reordering of the primacy of certain concepts (such as qubit and spin) for outreach purposes, where core concepts in QM might not be core concepts in QT, and vice versa. The results of this study provide valuable insights for those interested in learning more about this rapidly-evolving field.

Keywords: quantum technologies, outreach, education, public engagement, scientific culture, science communication

INTRODUCTION

The Advent of Quantum Technologies

The *second quantum revolution* (Dowling and Milburn, 2003) has been ongoing since the late 90s as advances in our understanding of quantum mechanics, as well as the development of new technologies for controlling and manipulating single/individual quantum systems, have been yielding increasing outputs in terms of scientific publications, patents, and start-ups (Seskir and Aydinoglu, 2021; Seskir and Willoughby, 2023; Seskir et al., 2022a). Currently, there are at least 25 enacted national and regional initiatives on QT (QURECA, 2022) with approximately $30B of public funding allocated to the field until 2030. Many in the field now believe that raising awareness is the absolute minimum that needs to be done (Roberson, 2023).

A central problem in raising awareness of emerging technologies such as QT is reaching members of the public, in particular school students, when there is no standard representation of QT in national curricula (Faletic et al., 2023). Those of school age will compose the future quantum workforce, and thus it might be beneficial if they are

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inspired from early on, that they may begin their journey towards the industry. Furthermore, even those with no future education in STEM fields will live in a society dramatically influenced by QT (Vermaas, 2017), and it is essential that they are accepting of and open to the changes it will bring, rather than suffering from hype and misinformation which could substantially damage how we navigate the modern "society of acceleration" (Rosa, 2010; West and Bergstrom, 2021).

Quantum Technologies Education for Everyone

To this end, increasing efforts are going into the public communication, or *outreach*, of QT worldwide (e.g Italian Quantum Weeks, 2022; World Quantum Day, 2022). Innovative means of bringing quantum physics and technologies out of the lab to public audiences, such as through experimental demonstrations (Gow et al., 2018; 2022; Posner et al., 2018), artistic expressions (Hutchinson, et al., 2015; Decaroli & Malinowski, 2022), games and interactive tools (Wootton, 2017; Cantwell, 2019; Ahmed, 2021; Seskir et al., 2022b; Migdał et al., 2022; La Cour et al., 2022; Piispanen et al., 2022), and other novel methods (Goorney et al., 2022) have been developed as QT are becoming more and more realised.

With more time and energy serving this goal, it is now of essential importance that outreach is taken seriously for what it is - a kind of non-formal education, which may be the best tool we have to address the problems of hype and misinformation (Mackay et al., 2020). Educators and practitioners must be equipped with guidelines and best practices for how best to make use of limited time available in outreach activities. Addressing this need, the project Quantum Technologies Education For Everyone (QuTE4E), a pilot of the Quantum Technology Education (QTEdu, 2022) community initiative, ran for one year between Autumn 2021 and 2022. In QuTE4E, QT educators, researchers, and industry stakeholders have come together under a shared passion for communicating this rapidly developing field to the public.

The goals of the pilot have been twofold. First, it has been to unite the community and draw on the diverse knowledge, interests, experiences, and resources of its participants to pioneer a new approach to outreach we call *Physics Outreach Research (POR)*, based in the field of QT. Second was to utilise this research-based approach to develop practical guidelines and methods which may be used for education outside of the classroom, such as guidelines for quantum science and technologies outreach and a concept inventory for QT outreach. Contributing research in this direction includes a framework for the narrative structure of activities (Goorney et al., 2022), a compendium of useful tools for practitioners (Seskir et al., 2022b), and an evaluation of outreach activities conducted through the pilot (Chiofalo et al., 2022). One of the research activities was to carry out a survey study to determine the Stakeholders, Opportunities, Problems, Solutions, and Concepts for Quantum Outreach, which ran between September 2021 and June 2022. Here we introduce the findings of the essential Quantum concepts which are needed in informal education activities and present a classification scheme which may be used by educators and practitioners to inform what they choose to outreach. We then consider the implications of these findings for designing and carrying out QT outreach. As the need for informal education in QT increases, and outreach events increase in both number and diversity, this study may help developers and practitioners to increase their impact in this important field.

Speaking the Quantum "Language": The Discipline-Culture Approach

One particularly interesting aspect of QT is its mystifying "culture", particularly with respect to the Quantum Physics which underlies it. Educators have considered this implicitly many times, referring to the unique "language" of quantum physics (Decaroli and Malinowski, 2022; Bouchée et al., 2022). One may consider that as a discipline, quantum physics has its own narrative, including a historical development (Weissman et al., 2018) and numerous interpretations (Cabello, 2017), which separates it from most other fields. Such is true of other areas too, such as General Relativity. Nowhere else in science would one refer to the "warping of spacetime" (Kersting and Steier, 2018; Woithe and Kersting, 2021) in regular language.

In fact, the unique "culture" is a core part of every scientific discipline, all of which are characterised by their own narratives. Such an interpretation forms the basis of the *Discipline-Culture* (DC) *framework* first introduced by Tseitlin and Galili (2005), which arose precisely from an examination of the nature of sciences as composed of seemingly distinct disciplinary fields, each with their own content, narratives, and languages. In the DC framework, scientific fields are organised into three components:

i) The *Nucleus*, in which are held the core, paradigmatic concepts which define the properties of the field
ii) The *Body* of working everyday applications of these principles
iii) The *Periphery* of alternative viewpoints and historical accounts.

Every scientific discipline is composed of elements of all three, and Physics as a whole is built up from a continuous dialogue of numerous interacting discipline-cultures, whose periphery shifts over time, resulting in an ever-changing landscape (**Figure 1**).

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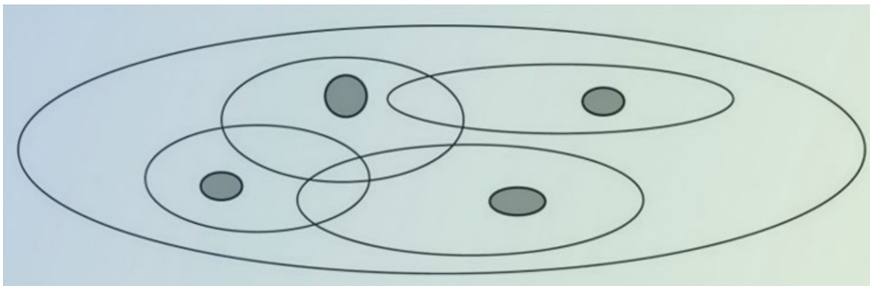

Figure 1. Physics as an interaction of several discipline-cultures (adapted from Tseitlin et al., 2005)

In Quantum Physics, the DC framework has been previously used by Weissman et al. (2018, 2022) to compare concepts included in formal education curricula. In the context of non-formal education, Goorney et al. (2022) proposed it as the backbone to a narrative approach, *culturo-scientific storytelling*, which takes participants on a journey through the DC, with benefits for engagement and the development of futures thinking skills (Levrini et al., 2019). In fact, we may consider the goal of non-formal education to be this introduction into the discipline-culture, resulting in students and citizens of the public getting familiarised with the language of the field, and thus not be prone to the hype and misinformation associated with misinterpretation of its culture via misuse of field specific language. In this research, we take community input to this end in the form of a survey around most important quantum concepts for public awareness, and use the DC framework as a lens through which to uncover the nuances of this discussion.

METHODOLOGY

In this work, we employed an iterative survey with open ended questions in earlier stages for exploratory purposes followed by grading in a later stage for rank ordering purposes. This process allows for expert input not only in the results of the study, but also in constituting the questions, ensuring they are representative. In the QT community, this method is also being utilised to identify the key topics for quantum mechanics in secondary schools (Krijtenburg-Lewerissa et al., 2019), and to create a competence framework and qualification profiles for the QT workforce (Gerke et al., 2020; 2022; Greinert et al., 2023).

Our study consisted of three rounds, each of which was disseminated to the QTEdu community of around 400 members through email newsletters and shared internally within the QuTE4E pilot. The preliminary round took place between September and November 2021 and involved 13 participants who filled out a Google forms document with open-ended questions. Based on the outcomes of the preliminary round, the first round of the survey was formulated using the SoSci Survey tool. **Figure 2** shows the timeline of the QuTE4E survey.

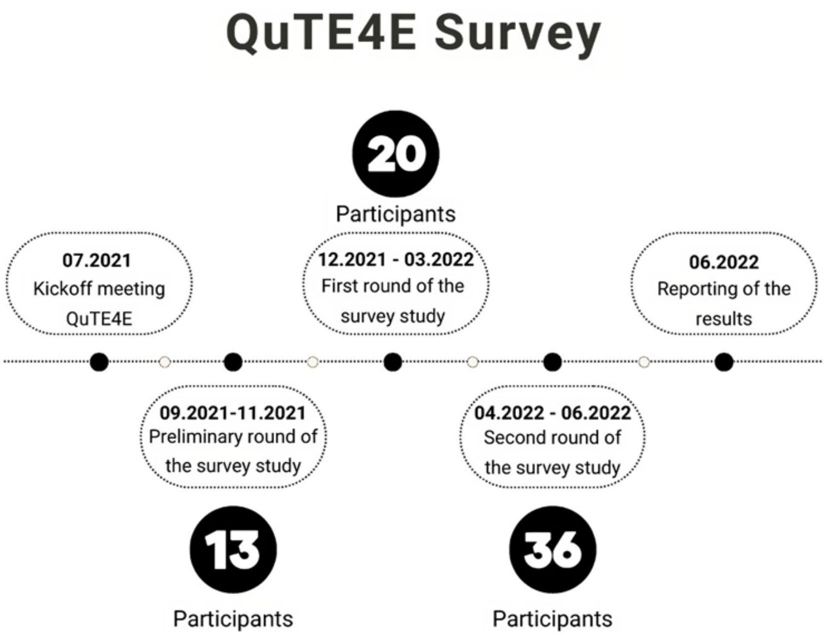

Figure 2. The timeline of the QuTE4E survey

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Table 1. Comparison of preliminary and final round of questions

Preliminary round questions	Second (final) round questions
Which essential concepts of quantum physics should be utilized for outreach activities in quantum technologies?	Please rate the concepts/approaches provided below in terms of their usefulness to be utilized for outreach activities in quantum technologies.

The study underwent several small alterations between the different versions of the survey. Table 1 illustrates the format of the question asked in the preliminary round and the final version. One example of such a change is the addition of the "Don't know" option in the Likert scale, which was only included in the final round following a suggestion from a participant in the first round. Another difference between the first and second rounds was the inclusion of a "country" option in the background section of the survey for participants, which was only present in the final round. For the questions a five-point Likert scale was used ranging between the options "Not important at all" to "Very important," with an added option of "Don't know." These modifications were made in an effort to continuously improve the survey and gather more comprehensive and accurate data.

The lists of items to be included on the questions were formulated in the following manner: initial lists of these items were created using the outputs of the preliminary round of the study, where experts were asked to put in their replies to open-ended questions. Following this, in the first round of the study the results of the preliminary round were presented to the participants to be rated and additional items were allowed to be added by them. The items to be rated in the second round were then composed of those suggested in the preliminary round, along with those added in the first round. Through this, the iterative survey method allowed us to use community input not only in the results of the study, but also in constituting the questions. This helped to ensure that items chosen in the final round were representative, as they were provided by multiple experts (those completing the preliminary and first rounds), rather than only the researchers who created the survey, as would have been the conventional survey method.

Finally, there are three main points of limitations to be kept in mind when utilising the outcomes of this study. First, the study inputs and outputs were generated combining the discussions within the pilot project, and a survey study comprising three rounds of surveys with a total of 36 participants in the final round. Therefore, the findings presented here should not be taken as an exhaustive and complete representation of the community, but only a first step towards further understanding the intricacies of QT outreach. Second, as both the field of QT and the pressing needs of our world are rapidly changing and as the final round of this study took place between April and June 2022, the temporal limitation should always be noted. Finally, as the QuTE4E pilot project mainly consisted of researchers from the EU region, the outcomes are biassed towards representing this region's perspectives.

FINDINGS

In this section, we provide further details of the final survey and participants, present our findings and some comments of the participants obtained from the final round of the study. Most discussions on the findings are reserved for the Discussion section.

During the final round of the study, a total of 446 clicks were made to the survey and 36 participants completed it in full, which might be attributable to the length of the survey. Only the 36 participants (out of the 400 members) who completed the survey in full were taken into account in the end for our analysis, and we do not know which kind of experts answered beyond the data provided by them on country, type of positions, and years of experience in QT outreach efforts in the demographics section of the survey. These participants were geographically distributed as follows: 21 from the EU countries, four from Southeast Asia (India and Malaysia), seven from the UK and the USA, and four from other countries (Ethiopia, Tunisia, Turkey, and Zimbabwe).

In terms of their outreach positions, three categories were identified: academic, industry, and non-profit. Of the 36 participants, a total of seven selected one or more of these options, with only one participant (from Tunisia) selecting Outreach (non-profit) as their sole "position." The remaining six participants who had outreach responsibilities also held at least one other non-outreach position. In total, 10 out of 36 participants reported having multiple positions or responsibilities, with six of these participants having outreach responsibilities as well. It was also observed that PhD students who were involved in outreach efforts typically had at least one other responsibility as a researcher or administrative staff member.

In terms of experience in QT outreach and education, four out of the seven participants with outreach-related positions had 1-5 years of experience, one had *"Less than one year,"* one had *"5-10 years,"* and one had *"10-20 years."* In total, three of the participants had less than one year, 21 of the participants had 1-5 years, two participants had 5-10 years, four participants had 10-20 years, four participants had 20+ years of experience in QT outreach or education while two of the participants noted that they are not involved in QT outreach or education. A summary of this can be found in Table 2.

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Table 2. Distribution of QT outreach and education experience of the participants

	Less than one year	1-5 years of experience	5-10 years of experience	10-20 years of experience	20+ years of experience
# of participants with outreach experience (34)	3	21	2	4	4
# of participants with outreach positions (7)	1	4	1	1	0

In the survey, we asked the participants to rate the concepts provided in terms of their usefulness to be utilised for outreach activities in QT. The results are rank-ordered in **Table 3**, where the highest ranked items are located at the top of **Table 3**, and the lowest ranked are at the bottom. In addition, the authors assigned each a position within the *discipline-culture* of quantum physics, based on the findings of Weissman et al., (2018 and 2022), discussed below in the *Discussion* section.

Table 3. Concepts to be utilised for QT outreach activities (rated in terms of their usefulness), and their position in the discipline-culture of quantum physics ("Not important at all" = 1, "Very important" = 5)

Concepts	Grade
Superposition (**Nucleus**)	4.72
Measurement (**Nucleus**)	4.69
Quantum state (**Nucleus**)	4.69
Qubit (**Body**)	4.58
Entanglement (**Nucleus**)	4.39
Interference (**Body**)	4.31
Technological concepts (like quantum computers) (**Body**)	4.22
Probability amplitude (**Nucleus**)	4.19
Quantum coherence/decoherence (**Body**)	4.06
Physical qubit platforms (atoms/ions, photonics, superconductors, etc.) (**Body**)	4.03
How the theory predicting only probability and uncertainty leads to technology of highest precision and control (**Periphery**)	4.00
Concepts that can be explained using binary logic and arithmetic (**Periphery**)	3.97
Algorithms (**Body**)	3.80
Classical computing (**Periphery**)	3.75
Tunneling (**Body**)	3.69
Quantum optics concepts (**Body**)	3.69
Spin (**Nucleus**)	3.67
Bell test (**Body**)	3.51
Quantization (**Nucleus**)	3.17
Complexity theory (**Periphery**)	3.03

The concepts of superposition, measurement, quantum state, qubit, and entanglement are top five. Meanwhile, more QM-heavy concepts such as spin, quantization, Bell test, tunnelling, quantum optics ranked rather low. Complexity theory, a CS-heavy concept, is also ranked the least useful concept.

DISCUSSION

Before any consideration of implications arising from our results, we first highlight that the sample size of the study was limited. However, as we discuss here, the findings raise some interesting ideas which may still provide valuable insights for QT outreach practitioners, developers and decision-makers. One particularly notable outcome of the study was highlighting the ongoing tension within the community surrounding the perception of QT as a field primarily for physics and physicists versus a more interdisciplinary field in which computer science and other disciplines play a central role. This tension became evident in our community meetings for the reporting of the results of the study, as those (primarily) from quantum physics education and outreach backgrounds were questioning the results, for example not believing that spin as a concept could have been ranked so low. In comparison, those more focused on QT and quantum computing education and outreach argued against the utilisation of spin as a concept for outreach purposes, which led to fruitful discussions and our belief of the necessity of introducing the discipline-culture framework into QT outreach efforts. Furthermore, this tension has been observed in the literature on quantum computing since the early 2000s (Mermin, 2003), is particularly notable in the field of quantum computing, which has seen the emergence of computer science-oriented approaches to teaching (Yanofsky and Mannucci, 2008) and outreach and education activities (Salehi et al., 2022). In these approaches, quantum computing is often presented as a generalisation of probabilistic computing, a perspective popularised in Scott Aaronson's book "Quantum Computing Since Democritus" (2013). However, it should be noted that quantum computers are still in their early stages of development, and writing effective quantum algorithms often requires taking into account the specific physical hardware being used. This highlights the need for interdisciplinary collaboration and a balanced approach to QT outreach and education that takes into account the perspectives and expertise of multiple disciplines.

Concepts and Approaches

First, we note that the top three most important concepts rated for inclusion are: Superposition, Measurement, and the Quantum State. All of these are considered core concepts in the field and some of the defining characteristics of quantum systems, thus lying in the Nucleus of the DC. Indeed, they can be found in the Postulates of Quantum Mechanics (Sakurai, 2017). These ideas are some of the most fascinating that can be encountered in Physics, and have inspired works of art (Levrier, 1997), science fiction, and several generations of scientists. It is possible that the participants rated these highly for their role inspiring the public with interest in the field.

After the concepts in the Nucleus, the next most popular for inclusion are those in the Body, in particular Qubits, Technological concepts (like computing), and Interference. One explanation for this may be that both investment and public interest in Quantum Technologies is strongly skewed towards Computing over the other fields of Sensing and Communication (Mckinsey, 2022), resulting in Qubits and computing concepts being rated greater in value than others. Interference, on the other hand, is very often discussed alongside Superposition and Measurement, which may explain its inclusion among the most important concepts in the Body of the DC.

It is also interesting to see that aspects of the Periphery, such as Complexity Theory and Classical Computing, are generally rated with lower importance than those concepts in the Body and Nucleus. Previous work (Weissmann et al., 2018; Levrini et al., 2014) has identified historical and alternative viewpoints of the field to hold great value in promoting skills such as scientific thought and future-awareness. However, study participants may have considered these benefits to be less impactful than the "wow factor" associated with some of the Nuclear concepts. On balance, given the limited time and resources available, this may explain the relatively low importance given to the concepts in the Periphery of the DC.

Finally, given the debate between whether QT lies within the domain of Physics, Computer Science, or elsewhere, it is interesting to consider whether quantum physics or quantum information science (QIS) is the relevant DC to take into account for QT. The Qubit can be considered as a core Nuclear concept for QIS while it is a concept located in the Body of quantum physics. In the discussions and comments collected during the study, we noted that the discourse around QT was strongly dominated by physics and physicists, a finding consistent with previous bibliometric studies (Seskir and Aydinoglu, 2021). However, the idea that QT builds largely on other fields was also highlighted in some responses, suggesting that this debate is far from being resolved.

> Participant: "Globally, this study seems to assume quantum technologies is only a problem of physics and/or physicists. A quite large part of the work involves computer scientists (algorithmics, quantum software, language) and there are already problems in communicating this towards the physics community. This difficulty of communication goes both ways."

One particular point of discussion within the pilot on our findings regarded the concept of Spin. Spin was ranked rather low in terms of usefulness for QT outreach activities, which surprised some of the outreach and education practitioners in the project. However, outreach practitioners, particularly those working in the field of quantum computing and programming, identified the difficulty of effectively utilising the concept in an outreach context. The way that Spin is typically communicated to a non-expert audience through the use of analogies such as a spinning ball can be confusing and misleading, as Spin is not a physical property in the same way that an object spinning on an axis is. Additionally, much of the practical value of introducing the concept is in introducing Qubits and thus applications such as quantum algorithms. However, these can still be understood without the concept of Spin, and thus on balance it may be better to avoid the concept in outreach settings, for risk of miscommunication and better use of limited time.

The final insight we would like to highlight from this study is that QT outreach should be diversified to meet the needs of different target audiences with respect to different target goals, as it is not a field emanating from a single discipline, but in fact has several divergent background disciplines that it is built upon. A recurrent theme that emerged during our conversations within the pilot and is clear from the resulting concepts in the study, was whether communicating quantum mechanics is a necessity to effectively communicate QT to non-expert audiences. On one hand, there is a push to make quantum theory understandable as the enigmatic source of QT (Vermaas, 2017), on the other hand, there is an added benefit of considering each QT and their applications by being specific (Coenen, et al., 2022). This suggests that the appropriate role and use of quantum mechanics and theory in QT outreach and education is a topic that deserves further attention and discussion within the community.

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CONCLUSION

In this study we presented a portion of the findings of a survey study that was conducted as part of the QuTE4E pilot under the QTEdu CSA of the European Quantum Flagship program titled "Quantum Outreach: Stakeholders, Opportunities, Problems, and Solutions", and an analysis of the findings related to the rank-ordering of the concepts for their utility in QT outreach activities through the *discipline-culture* framework. The primary finding of our study is that QT outreach and QM outreach, although having much in common, diverge in their relation to certain concepts (such as qubit and spin). This hints that as QT becomes more of a normalised and widespread set of technologies in the public domain and democratised (Seskir et al., 2023), further diversification of outreach methods moving away from QM outreach methods particularly relating to non-physicist audiences are needed.

This study is foundational in the new approach the QuTE4E pilot calls *Physics Outreach Research*. We believe that outreach, as non-formal education, requires the same degree of research-based attention and evaluation as classroom STEM teaching has had for decades. Our results are a first step in this important direction, unveiling several tensions in the community. It is natural then that while these debates continue, there can be no single best approach for which concepts to include in QT outreach activities. However, we encourage educators to reflect on the purpose for which they are communicating QT. In doing so, they may uncover the most effective approaches for their own needs, selectively incorporating concepts from the Nucleus, Body, and Periphery of QT. This research may provide valuable insights and guidance for individuals and organisations engaged in quantum outreach efforts, as well as those interested in learning more about this rapidly-evolving field.

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REFERENCES

Aaronson, S. (2013). *Quantum Computing Since Democritus*. Cambridge, MA, USA: Cambridge University Press. https://doi.org/10.1017/CBO9780511979309

Ahmed, S. Z. (2021). *Quantum Games and Simulations: Applications in education, outreach, and research*. Aarhus Universitet.

Bøe, M. V., Henriksen, E. K. and Angell, C. (2018). Actual versus implied physics students: How students from traditional physics classrooms related to an innovative approach to quantum physics. *Science Education*, 102(4), 649–667. https://doi.org/10.1002/sce.21339

Bouchée, T., de Putter-Smits, L., Thurlings, M. and Pepin, B. (2022). Towards a better understanding of conceptual difficulties in introductory quantum physics courses. *Studies in Science Education*, 58(2), 183–202. https://doi.org/10.1080/03057267.2021.1963579

Cabello, A. (2017). Interpretations of quantum theory: A map of madness, in O. Lombardi, S. Fortin, F. Holik and C. López (eds.), *What is Quantum Information?* (pp. 138–144). Cambridge: Cambridge University Press. https://doi.org/10.1017/9781316494233.009

Cantwell, C. (2019). Quantum chess: Developing a mathematical framework and design methodology for creating quantum games. *arXiv*. https://doi.org/10.48550/arXiv.1906.05836

Chiofalo, M. L., Foti, C., Michelini, M., Santi, L. and Stefanel, A. (2022). Games for teaching/learning quantum mechanics: A pilot study with high-school students. *Education Sciences*, 12(7), 446. https://doi.org/10.3390/educsci12070446

Coenen, C., Grinbaum, A., Grunwald, A., Milburn, C. and Vermaas, P. (2022). Quantum technologies and society: Towards a different spin. *NanoEthics*, 16(1), 1–6. https://doi.org/10.1007/s11569-021-00409-4

Decaroli, C. and Malinowski, M. (2022). "Do you speak quantum?" A quantum physics and art exhibition. *Optical Engineering*, 61(08), 081807. https://doi.org/10.1117/1.oe.61.8.081807

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Dowling, J. P. and Milburn, G. J. (2003). Quantum technology: the second quantum revolution. *Philosophical Transactions of the Royal Society of London. Series A: Mathematical, Physical and Engineering Sciences*, 361(1809), 1655–1674. https://doi.org/10.1098/rsta.2003.1227

Faletic, S., Bitzenbauer, P., Bondani, M., Chiofalo, M., Goorney, S., Krijtenburg-Lewerissa, K., Mishina, O., Muller, R., Pospiech, G., Ercan, I., Malgieri, M., Merzel, A., Michelini, M., Onorato, P., Pol, H., Santi, L., Seskir, Z. C., Shrson, J., Stadermann, K., … and Zabello, O. (2023). Contributions from pilot projects in quantum technology education as support action to quantum flagship. *arXiv*. https://doi.org/10.48550/arXiv.2303.07055

Gerke, F., Müller, R., Bitzenbauer, P., Ubben, M. and Weber, K. (2022). Requirements for future quantum workforce – A Delphi study. *Journal of Physics: Conference Series*, 2297(1), 012017. https://doi.org/10.1088/1742-6596/2297/1/012017

Gerke, F., Müller, R., Bitzenbauer, P., Ubben, M. and Weber, K.-A. (2020). Quantum Awareness im Ingenieurwesen: Welche Kompetenzen werden in der Industrie von morgen gebraucht? [Quantum Awareness in Engineering: What skills will be needed in tomorrow's industry?], *PhyDid B - Didaktik Der Physik - Beiträge Zur DPG-Frühjahrstagung*, *1*. Available at: https://ojs.dpg-physik.de/index.php/phydid-b/article/view/1034

Goorney, S., Foti, C., Santi, L., Sherson, J., Yago Malo, J. and Chiofalo M. L. (2022). Culturo-scientific storytelling. *Education Sciences*, 12(7), 474. https://doi.org/10.3390/educsci12070474

Gow, P. C., Gates, J. C., Bannerman, R. H., Nunn, J., Posner, M. T., Mennea, P. L. and Smith, P. G. (2018). Taking quantum entanglement out of the lab. *Optics Education and Outreach V*, 10741. https://doi.org/10.1117/12.2321079

Greinert, F., Müller, R., Bitzenbauer, P., Ubben, M. S. and Weber, K.-A. (2023). Future quantum workforce: Competences, requirements, and forecasts. *Physical Review Physics Education Research*, 19, 010137. https://doi.org/10.1103/PhysRevPhysEducRes.19.010137

Hutchinson, D. A. W., Aitchison, H., Cameron, B. and Currin, J. (2015). Artfully exploring quantum physics. *Junctures*, 16, 11–20.

Italian Quantum Weeks. (2022). *Italian Quantum Weeks*. Available at: https://quantumweeks.it

Kersting, M. and Steier, R. (2018). Understanding curved spacetime. *Science & Education*, 27(7), 593–623. https://doi.org/10.1007/s11191-018-9997-4

Krijtenburg-Lewerissa, K., Pol, H. J., Brinkman, A. and van Joolingen, W. R. (2019). Key topics for quantum mechanics at secondary schools: A Delphi study into expert opinions. *International Journal of Science Education*, 41(3), 349–366. https://doi.org/10.1080/09500693.2018.1550273

La Cour, B. R., Maynard, M., Shroff, P., Ko, G. and Ellis, E. (2022). The virtual quantum optics laboratory, in *2022 IEEE International Conference on Quantum Computing and Engineering*. Broomfield, CO, USA, 677–687. https://doi.org/10.1109/qce53715.2022.00091

Levrier, G. (1997). A painter's thesis: Quantum physics as an inspiration for art. *Leonardo*, 30(4), 268–269. https://doi.org/10.2307/1576472

Levrini, O., Bertozzi, E., Gagliardi, M., Tomasini, N. G., Pecori, B., Tasquier, G. and Galili, I. (2014). Meeting the discipline-culture framework of physics knowledge: A teaching experience in Italian secondary school. *Science and Education*, 23, 1701–1731. https://doi.org/10.1007/s11191-014-9692-z

Levrini, O., Tasquier, G., Branchetti, L. and Barelli, E. (2019). Developing future-scaffolding skills through science education. *International Journal of Science Education*, 41(18), 2647–2674. https://doi.org/10.1080/09500693.2019.1693080

Mackay, S. M., Tan, E. W. and Warren, D. S. (2020). Developing a new generation of scientist communicators through effective public outreach. *Communications Chemistry*, 3(1), 76. https://doi.org/10.1038/s42004-020-0315-0

Mckinsey. (2022). Quantum Technology Monitor, *Mckinsey*. Available at: https://www.mckinsey.com/capabilities/mckinsey-digital/our-insights/quantum-computing-funding-remains-strong-but-talent-gap-raises-concern

Mermin, D. N. (2003). From Cbits to Qbits: Teaching computer scientists quantum mechanics. *American Journal of Physics*, 71(1), 23–30. https://doi.org/10.1119/1.1522741

Migdał, P., Jankiewicz, K., Grabarz, P., Decaroli, C. and Cochin, P. (2022). Visualizing quantum mechanics in an interactive simulation – Virtual lab by quantum flytrap. *Optical Engineering*, 61(8), 081808. https://doi.org/10.1117/1.oe.61.8.081808

Piispanen, L., Pfaffhauser, M., Kultima, A. and Wootton, J. (2022). Defining quantum games. *arXiv*. https://doi.org/10.36227/techrxiv.23507892

Posner, M. T., Mennea, P. L., Gow, P. C., Bannerman, R. H., Berry, S., Smith, D. H. and Gates, J. C. (2018). Taking large optical quantum states out of the lab: Engaging pupils and the public on quantum photonics sciences. *Optics Education and Outreach V*, 10741. https://doi.org/10.1117/12.2319391

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QTEdu Quantum Technology Education. (2022). QTEdu Quantum Technology Education. Available at: https://qtedu.eu

QURECA. (2022). Overview on quantum initiatives worldwide – Update 2022, *QURECA*. Available at: https://qureca.com/overview-on-quantum-initiatives-worldwide-update-2022/

Roberson, T. (2023). Talking about responsible quantum: "Awareness is the absolute minimum that … We need to do". *Nanoethics*, 17, 2. https://doi.org/10.1007/s11569-023-00437-2

Rosa, H. (2010). *Alienation and Acceleration: Towards a Critical Theory of Late-modern Temporality*. NSU Press.

Sakurai, J. and Napolitano, J. (2017). *Modern Quantum Mechanics*. Cambridge: Cambridge University Press. https://doi.org/10.1017/9781108499996

Salehi, Ö., Seskir, Z. and Tepe, İ. (2022). A computer science-oriented approach to introduce quantum computing to a new audience. *IEEE Transactions on Education*, 65(1), 1–8. https://doi.org/10.1109/TE.2021.3078552

Seskir, Z. and Aydinoglu, A. (2021). The landscape of academic literature in quantum information technologies. *International Journal of Quantum Information*, 19(02), 2150012. https://doi.org/10.1142/S021974992150012X

Seskir, Z. C. and Willoughby, K. W. (2023). Global innovation and competition in quantum technology viewed through the lens of patents and artificial intelligence. *International Journal of Intellectual Property Management*, 13(1), 40–61. https://doi.org/10.1504/IJIPM.2021.10044326

Seskir, Z. C., Korkmaz, R. and Aydinoglu, A. U. (2022a). The landscape of the quantum start-up ecosystem. *EPJ Quantum Technology*, 9, 27. https://doi.org/10.1140/epjqt/s40507-022-00146-x

Seskir, Z. C., Migdał, P., Weidner, C., Anupam, A., Case, N., Davis, N., Decaroli, C., Ercan, İ., Foti, C., Gora, P., Jankiewicz, K., La Cour, B. R., Malo, J. Y., Maniscalco, S., Naeemi, A., Nita, L., Parvin, N., Scafirimuto, F., Sherson, J. F., . . . and Chiofalo, M. (2022b). Quantum games and interactive tools for Quantum Technologies Outreach and education. *Optical Engineering*, 61(8), 081809. https://doi.org/10.1117/1.oe.61.8.081809

Seskir, Z. C., Umbrello, S., Coenen, C. and Vermaas, P. (2023). Democratization of quantum technologies. *Quantum Science and Technology*, 8(2), 024005. https://doi.org/10.1088/2058-9565/acb6ae

Tseitlin, M. and Galili, I. (2005). Physics teaching in the search for its self: From physics as a discipline to physics as a discipline-culture. *Science Education*, 14, 235–261. https://doi.org/10.1007/s11191-004-7943-0

Vermaas, P. E. (2017). The societal impact of the emerging quantum technologies: a renewed urgency to make quantum theory understandable. *Ethics and Information Technology*, 19(4), 241–246. https://doi.org/10.1007/s10676-017-9429-1

Weissman, E. Y., Merzel, A., Katz, N. and Galili, I. (2018). Teaching quantum mechanics in high-school – Discipline-culture approach. *Journal of Physics: Conference Series*, 1287, 012003. https://doi.org/10.1088/1742-6596/1287/1/012003

Weissman, E. Y., Merzel, A., Katz, N. and Galili, I. (2022). Phenomena and principles: Presenting quantum physics in a high school curriculum. *Physics*, 4, 1299–1317. https://doi.org/10.3390/physics4040083

West, J. D. and Bergstrom, C. T. (2021). Misinformation in and about science. *Proceedings of the National Academy of Sciences*, 118(15), e1912444117. https://doi.org/10.1073/pnas.1912444117

Woithe, J. and Kersting, M. (2021). Bend it like dark matter! *Physics Education*, 56(3), 035011. https://doi.org/10.1088/1361-6552/abe09c

Wootton, J. (2017). Getting the public involved in quantum error correction. *arXiv*. https://doi.org/10.48550/arXiv.1712.09649

World Quantum Day. (2022). World Quantum Day. Available at: https://worldquantumday.org/

Yanofsky, N. S. and Mannucci, M. A. (2008). *Quantum Computing for Computer Scientists*. Cambridge, MA, USA: Cambridge University Press. https://doi.org/10.1017/CBO9780511813887

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