Requirements for future quantum workforce – a Delphi study

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Abstract. With new quantum technologies and new applications comes a new need for specialists, the new quantum workforce. This brings new challenges for education that the typical quantum mechanics courses for physicists do not address. Requirements for the future quantum workforce need to be collected and training programmes created. In between, there should be a European competence framework on which to build the training programmes. One goal of the European Flagship project QTEdu is to develop this framework for second-generation quantum technologies. The Delphi study presented here serves as a basis for this: The aim is to identify knowledge and competences in the field of quantum information technologies, which are partly already needed in industry today, but especially in the future.

1. Aim

The increasing relevance of quantum technologies in Europe [1] poses new challenges for the (university) education of specialists in this field - not only in physics, but also in engineering [2, 3]. One goal of our research is the development of a competence framework for second-generation quantum technologies within the European Quantum Flagship[6] project "Coordination and Support Action for Quantum Technology Education" (QTEdu CSA)[7]. On the basis of this framework, further educational concepts, (master) courses of study or optional specialisation subjects can be developed. The results of this study will be used to prepare said competence framework. One additional important aspect is also the extraction of applications that are deemed crucial for the future of the development of quantum technologies.

They can then in turn be used to determine requirements for physics teaching in order to lay the foundation for higher education. It is apparent that not only engineers will have to deal with quantum technologies in the future - moreover, pupils at school should already be made aware to the social relevance of quantum physics, which is consequently also a goal of the Quantum Flagship. Teachers of physics should therefore not only be able to solve the Schrödinger equation, but also acquire more general skills as they will appear in the competence framework. For this reason, experts with a teaching background were also included in our study.

Since this field is just forming, there is no work of this kind yet, meaning that we also aim to lay the foundation in this regard.

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[6] Quantum Flagship official website: qt.eu.
[7] Flagship project QTEdu CSA website: https://qt.eu/about-quantum-flagship/projects/education-coordination-support-actions/, project description: cordis.europa.eu/project/id/951787.

2. About the Study

Study design, methods of data analysis and information on the professional background of the participants are presented in this section.

2.1. Delphi Method

The Delphi method can be used to identify and qualify expert opinions and is characterized by the iterative process of questioning and feedback, which in turn forms the starting point for the next survey [4]. As the investigated field of second generation quantum technologies is new and therefore only a few experts can be interviewed, the study is broadly based and the Delphi method is used as it was deemed the most suitable way of collecting and structuring relevant empirical data. A strong point of this approach is that the experts can reflect and comment on other experts' opinions and statements without being influenced by group behaviour, paving the way for a potentially more diverse set of data.

The procedure of this study is shown in figure 1. In the pilot round around March 2020, a smaller group of experts answered mostly open questions. It gave an overview of this open field for the first time. The answers of the pilot round were then bundled and opinions collected. In the first main round, which took place in autumn 2020, these assessments were presented to a larger group of people than in the pilot for evaluation and completion. A second main round will be used for the final evaluation, so that on this basis the development of a competence framework will be possible. It will take place around spring 2020. Note that the Delphi method is exploratory, i.e. we aim to open up the new research field of QT workforce but we do not want to clarify concrete research questions

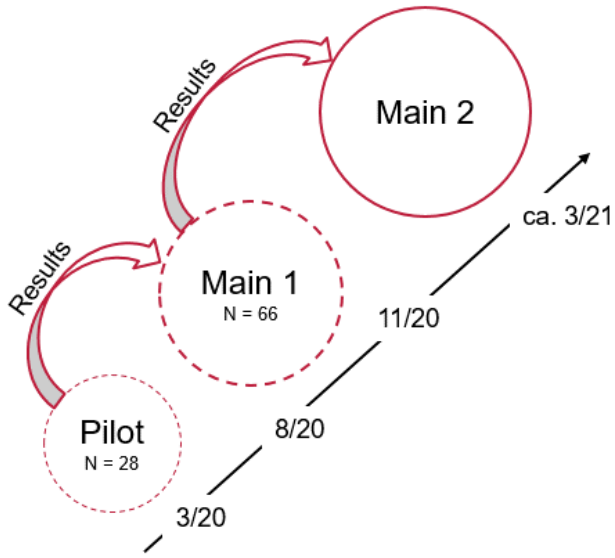

Figure 1. Study design and timetable.

2.2. Data analysis

There were two main types of data resulting from the pilot and the first main round. The first type is quantitative and comes from close-ended questions. The other type is qualitative data from open-ended questions. For these, a qualitative content analysis [5] was conducted using MaxQDA[8] version 12 and some exemplary answers were selected. Thereafter, the answers were categorised and for example, as shown in figure 2, these categories were then visualised by giving exemplary answers in the format "quote" (answer ID). According to Landis and Koch [6], intercoder reliability was substantial for all

[8] MaxQDA: software for qualitative and mixed methods research: maxqda.com.

categories (κ between 0.82 and 0.89) in the pilot round for 6 (represents 20%) randomly selected responses.

2.3. Participants
The questions on the professional background showed that in the pilot round, the smaller group of experts (N=28) mainly assigned themselves to science (almost 90%) or education (about 80%) and about 60% to research/development, while only 10-15% assigned themselves to industry/economy or computer science/IT.

In the first main round, the group size more than doubled (66 evaluable datasets). Now, 35-40% assigned themselves to industry/economy or computer science/IT, while the proportion of participants who assigned themselves to science or education decreased to 50-60%. Slightly more (approx. 65%) assigned themselves to research/development. Other areas were selected from less than 20%. Details are shown in table 1.

Table 1. Absolute number of participants who assigned themselves to the professional fields.

	Industry/ Economy	Computer science/ IT	Science	Education	Training/ Instructor	Research/ Development	Application/ Use	Other	N
Pilot	4	3	25	23	3	17	2	1	28
Main 1	24	22	40	33	5	41	10	2	65

3. Selected interim results
The future quantum workforce will be made up of people who work with quantum technologies, such as engineers, computer scientists, chemists, biologists, but who do not have such a strong (quantum) physics background as physicists. In order to summarise the knowledge and competence areas required for this group of people, a term is needed, and in the Flagship context the term “Quantum Awareness” is used. We discuss this term and identify possible alternatives with the help of expert opinions.

In addition, assessments of the relevance of the new quantum technologies, e.g. for industry, were collected. Some initial results on these relevance assessments of the pilot round have already been presented in [7] and are not the focus of this article.

3.1. Using the Flagship term “Quantum Awareness”
The term "Quantum Awareness" was introduced to denote a basic, phenomena-oriented understanding of quantum physics. However, this term is frequently associated with esotericism. Therefore, the use of this term was criticised in the pilot round.

Thus, in the main round 1, the experts had to answer the question whether this term should be used or what better terms the participants could think of. 29 participants wanted to stay with “Quantum Awareness”, while also 29 made other suggestions. Terms such as “Quantum Technology Awareness” (mentioned 4 times), “Quantum Knowledge” (2 times), “Quantum Readiness” (2) or “Quantum Literacy” (2) were suggested. In the second main round, these suggestions will now be rated in order to provide a term which is community-based.

3.2. Competences and contents for the future quantum workforce
In the pilot round, there were open-ended questions about which competences and contents would be necessary, desirable or less relevant for the future quantum workforce. These answers were subjected to a qualitative content analysis [4], which led to four areas of possible central competences and contents for future quantum workforce. Figure 2 shows these areas with exemplary answers in quotation marks and with the answer ID named, i.e. having the format "answer text" (ID).

The first area covers the basic principles or phenomena such as the measurement effects, superposition and entanglement or non-locality. But also the "standard" quantum mechanics including the harmonic oscillator or the Schrödinger equation were mentioned. In the second area, we clustered mathematics. The answers varied from very general (“Good background”) to more concrete (“Finite-dimensional complex Hilbert spaces”) or focusing on qubit or state description. The third section collects answers on the physics background. They include more general answers, concrete physics or technologies and even address awareness of the conceptual differences between classical and quantum physics and the fact that (first generation) quantum technologies are already in use. Finally, the last area includes answers regarding concrete applications or general answers to how they work and what the novelty is. In the overall picture, we see many answers in the first area on the basics principles, less on mathematics, a little more on the physical background and again less on concrete applications. This map was used in the main round 1 questionnaire as a suggestion for the formulation of more concrete competences.

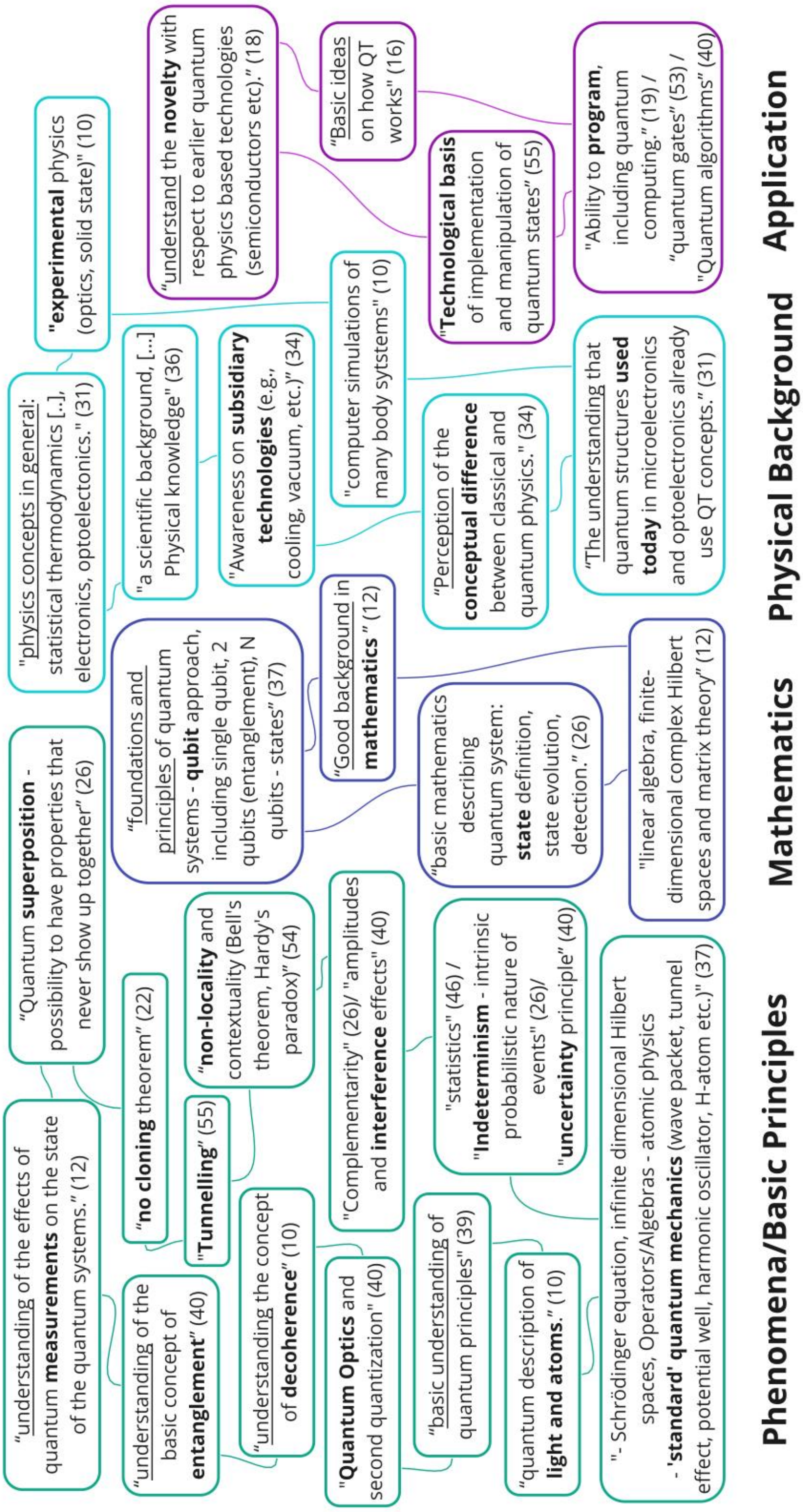

Figure 2. Competences and contents mentioned in the pilot.

3.3. Using pilot results in the first main round: first results from main 1

For the first main round, participants were shown the map (figure 2) for input/inspiration and asked to focus on a specific subfield. After naming such a subfield, they were asked to fill in a table to collect prestructured answers. The structure was a three-step format: addressing the concrete competence, what this competence would be useful for and what level of expertise would be needed. For the last item - the level of competence - the participants were asked to distinguish between "users" (U: ...) and "developers" (D: ...). An exemplary answer for the three aspects in a subfield was given to the participants and is shown in table 2. It can be read as follows: The "understanding of qubit operations and quantum gates" would be useful for "composing quantum algorithms and applying them to specific tasks", and the needed level of expertise would be for users to have a "deeper basic knowledge of the qubit concept and the effects of different operators on a formal-logical level. No specific knowledge of physical implementation of the operators and the qubits themselves is needed."

Table 2. Example for the prestructured question in the main round 1.

subfield	competence	useful for	needed level of expertise
quantum software development	understanding of qubit operations and quantum gates	composing quantum algorithms and applying them to specific tasks	U: deeper basic knowledge of the qubit concept and the effects of different operators on a formal-logical level. No specific knowledge of physical implementation of the operators and the qubits themselves is needed.

This question provided about 180 individual competences for 55 subfields. Three examples of these mentioned competences together with the chosen subfields are listed in table 3.

Table 3. Selected answers from the main round 1.

subfield	competence	useful for	needed level of expertise
quantum communication	understanding of quantum repeaters	determining quantum communication in fibre/free space	U: deeper basic knowledge of how quantum repeaters work. No specific knowledge of physical implementation of the specific hardware for quantum repeaters. D: deeper understanding of specific hardware and implementation for quantum repeaters
quantum-algorithm and quantum-software development	knowledge of existing quantum-algorithm concepts both for NISQ and FTQC	understanding and developing novel quantum algorithms	D: quantum-developers need to be fluent in all existing quantum-algorithm concepts so that they can build on those to develop novel algorithms or so that they can apply them to implement quantum solutions
quantum sensing	programming skills	Data processing	D: good programming skills will help to create an interface between the sensor and the PC to see the measurement result

The first evaluation step was to sort the subfields into the four areas "Phenomena/ Basic Principles", Mathematics", "Physical Background" and "Application" (see figure 2). Figure 3 shows in more detail the sorting of the participants' statements into these categories. The data shows a similar ratio as in the pilot round: again, there were many participants who focused on the basics, less on mathematics and a bit more on the physical background. But there were significantly more in the area of application, painting a more detailed picture of this topic.

Next is the analysis and categorisation of the about 180 individual competences. This allows the development of the concluding questionnaire and finally the creation of the competence framework on the requirements for the future quantum workforce.

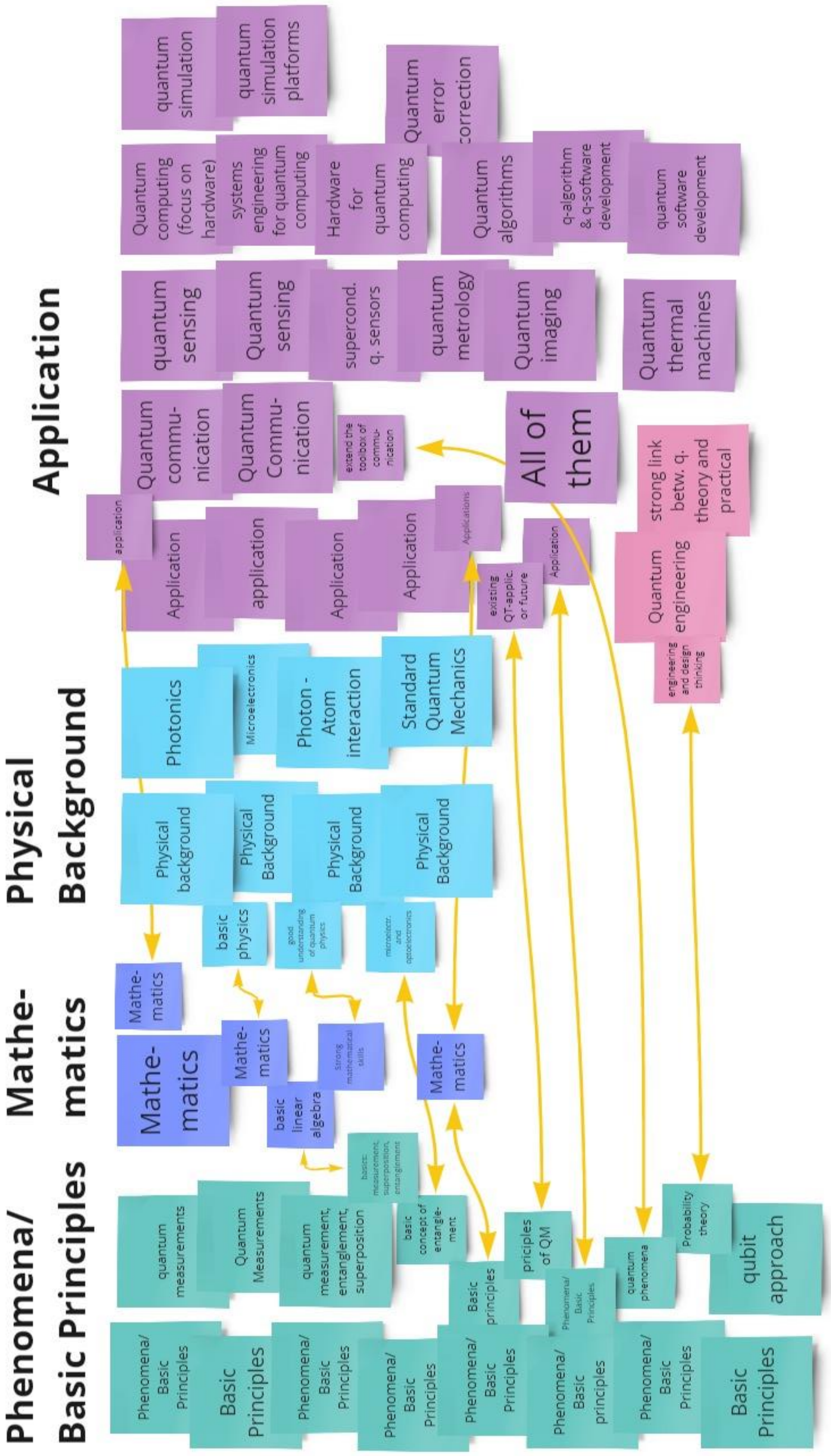

Figure 3. Sorting of the subfields mentioned in the main round 1 to give an impression of the ratio of answers per area. Some answers are shortened to selected fragments. Each large sticky note represents one answer, and the answers that fit into more than one area were divided into smaller sticky notes connected by an arrow.

3.4. Discussion

In this article, we present first insights into the qualitative results of a Delphi study. With the help of experts' opinions from research, industry and teaching, requirements for future quantum professionals will be extracted. These can act as a basis for further education and training programmes today, and especially in the future.

The results of the pilot and the first main round led to the identification of four preliminary competence areas, namely basic principles or phenomena, mathematics, physical background and applications. In line with the Delphi process, the second main round will be used to validate and refine these competence areas. The aim is also to tackle existing limitations that are closely interwoven with the Delphi research method: As is usual in Delphi studies, the researchers not only evaluate the collected data using recognised empirical methods but they also always intervene in the course of the Delphi study. For example, when it comes to the question of which results of the previous round are made available in the next questionnaire and which are not. Furthermore, the sample size has to be mentioned, and the fact that in the study reported here, mainly subjective assessments of the experts are collected. For this reason, it is crucial to - in a next Delphi round - increasingly quantify the insights gained so far so that preliminary results can be validated.

The results of this research may not only be of interest concerning the development of training programmes for future quantum workforce. Much more, it is in line with physics education research efforts on quantum physics as different teaching sequences on modern quantum physics in schools and universities have been developed. For example, teaching sequences using the qubit approach [8, 9] a quantum optics-approach [10, 11, 12], haptical approaches [13, 14], the double-well approach [15] or presenting characteristic traits of quantum mechanics [16]. With modern advances in quantum technologies, new potentials are now emerging for the teaching of modern quantum physics at all levels. In this respect, the results of our Delphi study could give this debate a further impulse.

4. Conclusion

The pilot round and the first main round of the Delphi study have already produced some interesting results. For example, the use of the term “Quantum Awareness” was criticized in the pilot round, which led to a question in the main round 1 to evaluate the use or find alternatives. Therefore, in the main round 2, selected proposals will be evaluated in competition with the above mentioned term.

In addition to that, the pilot round provided a first impression of possible competences and contents for the future quantum workforce. These were used as input or inspiration in the main round 1 to collect more concrete competences. The first analysis of the data of the main round 1 shows a plethora of competences deemed to be necessary by the experts and also confirms some of the points and observations extracted from the pilot round: the focus on quantum phenomena / basic principles with less mathematics and some knowledge in the physical background are needed. This also leads to the conclusion that in teaching quantum physics, it will be of utmost importance to not solely rely on mathematics, but also to facilitate the conceptual development regarding topics in quantum physics.

The second main round will now be used for some evaluations and additions so that the competence framework for the flagship project QTEdu CSA can be created based on broad expert opinion.

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