Strategic Agenda Summary: Education for QT

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Introduction

If Europe strives to be a leading force in the field of Quantum Technologies (QT), the need for quantum workforce and a well-educated society with knowledge and attitudes towards the acceptance of QT is imminent[1]. To provide a solid long term, sustainable implementation and progress of QT, a strong support of European Quantum Education is necessary. The challenge of an immense scaling-up in training and education while increasing interdisciplinarity and drawing acute attention to current and future corporate and societal needs can only be achieved with a comprehensive and coordinated effort. This endeavour has to establish an ecosystem bringing together all involved stakeholders.

Current Status

While quantum physics today is included in all university physics curricula and touched upon in school curricula in some European countries[2], this does not satisfy the needs for workforce ready to bring quantum technologies into engineering applications. In order to move the emerging field of quantum technologies closer to the needs of industry, a modern quantum education is needed throughout Europe, leading to quantum awareness and literacy for a broader range of school, university students and the workforce than today.

To address the challenge, the Quantum Community Network (QCN) has joined forces with leading physics education experts. As a result, a new community gathering educators, academics, communicators and industry representatives engaged in Quantum Science Education at all levels is emerging. This summary presents the first outcomes - envisioned pillars of the strategic education agenda within the flagship build upon the community needs (Oberkochen paper)[a] as well as first recommendation for the short and long term actions.

Advances in quantum technology education and educational research needed to meet future challenges

The most urgent challenge consists in developing effective training and educational modules for learners in the areas that traditionally do not get in touch with quantum physics (engineering, chemistry, mathematics, and biology). The conventional formal introduction to quantum physics, based on the concepts of 20th-century physics and geared towards quantum technologies 1.0, will not meet the needs of these audiences. An educational approach augmented by components conveying “quantum awareness” in the form of conceptual and intuitive understanding is needed. This is particularly pertinent since the quantum technological revolution brings a shift from observing and explaining naturally occurring systems to characterizing *engineering* systems with

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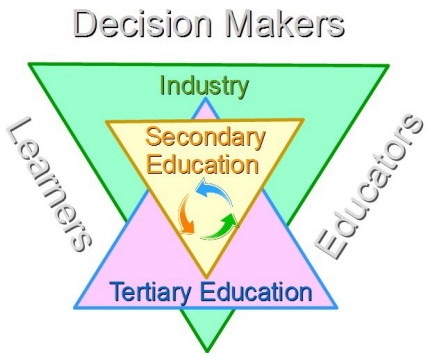
a “Education / Training and networking” section form “Supporting QT beyond H2020” summarizing the outcomes of the Quantum Flagship community meeting organized by the Coordination and Support Action QSA in Oberkochen (Germany) on 19.04. 2018 https://qt.eu/engage/resources/

optimal properties for a given application. This paradigmatic change in teaching and learning of quantum physics merges decades of Physics Education Research[3-13] and recently developed ICT-based approaches incorporating visualizations[14], simulations[15-23], education experiments[24,25], visitor's labs[26], and games[20,26,27]. This approach ensures a low barrier of entry for establishing the core concepts of quantum physics as well as the motivation for engaging with the more mathematical aspects of the topics. Research in physics education documents that a conceptual and intuitive approach will also enhance the quantum education of physics students [5,28-32]. The emphasis on the conceptual and intuition-based aspects of quantum physics will also foster a large-scale quantum awareness through implementation into the secondary (and eventually primary) school system and public engagement initiatives. Thus, the conceptual approach to quantum teaching will provide a valuable addition to the existing expert training that will enable fulfilling the maximal commercial potential of the quantum revolution.

A corresponding education and training program can be based on **three interconnected pillars** addressing different audiences:



1. **Secondary education**

   In secondary education, two targets need to be addressed: building general quantum awareness for all citizens and a sound preparation for the further education of future quantum engineers - quantum literacy. This pillar will address *in-service teachers* and *high school students* through new quantum curricula recommendations and teaching strategies, based on educational research, as well as *decision makers* in this sector (ministries of education, school organizations, e.g. for building a quantum curriculum). This pillar may be extended in the long term to include primary education as well.

2. **Tertiary education**

   In this pillar the main target is to cater for a modern quantum curriculum for future quantum technology specialists and as well as for researchers. By joining forces across Europe for building quality-controlled teaching resources and methods based on empirical educational research, quantum education at the tertiary level can greatly be enhanced. Target groups in this pillar are students at the Master and PhD levels in Quantum Science and Technology, related topics such as Mathematics, Engineering, Computer Science and Chemistry, pre-service teachers in these topics, as well as academic staff and decision makers (ministries, university and faculty boards).

3. **Industry**

   The main issue for industry is to develop concepts for getting the current workforce up level with current quantum technology. This involves decision makers in industry (CEOs, CTOs, SME organizations) as well as the members of the current workforce themselves which need special training courses to keep up with the progress of the second quantum revolution.

For the coordination of the efforts there is an immediate need for an Education Support and Coordination Action to 1) perform an extensive mapping of current and future requirements for education and training and 2) implement appropriate educational strategies into the related fields of engineering, chemistry, biology, computer science and other fields as well as 3) learn from and scale up advanced quantum technology training in physics[33] and connecting them to industries who would like to host their students for an internship to encourage and facilitate both sides to do it. To sustain this effort during the run of the education and training program, a persistent Education Coordination and Support Action will be needed to keep up to date the education research agenda and continually evaluate it against the evolving needs of the corporate applications. Moreover, there is a need to establish a Quantum Education Community Network, with a structure similar to the Quantum Community Network (QCN) that comprises representatives of the member states, to help coordinating the education activities/strategies between the Education Support and Coordination Action and the national initiatives.

Three years after the start of the program we will have

- Consolidated the needs and challenges of QT education on the (i) tertiary and (ii) secondary education level and of (iii) the quantum industry and formulated measures how these needs can be met (Education CSA).
- Built a repository of scientific literature and education studies, materials and resources, documenting and classifying learning activities and methods as well as listing key partners for QT education in Europe (separate COST action).
- Research the needs and feasibility of a QT curriculum for all levels, resulting in a proposed QT curriculum description and example teaching materials, teaching methods and evaluation concepts.
- Built a network platform and established regular international meetings between the QT research community, education research community, QT industry, educational authorities and further key partners
- Formulated pan-European framework for competency-based education standards modelled after the European DigCompEdu framework of digital competences for educators: A1-newcomers, A2-explorers, B1-integrators, B2-experts, C1-leaders, C2-pioneers.
- Pilot programmes for a Master degree in Quantum Technology for Engineers with student training in companies in each EU country.
- Used seed funding to specifically address the needs of member states, which have not yet a strong QT research community and/or industry of the 2nd quantum revolution to
    - Develop and evaluate formal and informal quality learning resources made accessible online at no cost (e.g. MOOCs, Jupiter Notebooks/Labs, Virtual Quantum Lab, gamification, QT demonstrators, apps…) using the most up-to-date online and virtual training technologies[16,17,34,35].
    - Provide hands-on learning experience which is reproducible/scalable at low cost[25,26,36] by developing laboratory experiments based on the most recent results of research in QT and physics education.
    - Develop exchange programmes (e.g. COST action, Erasmus Mundus+, mobility grants,...) to foster local expertise and support regional education clusters in tertiary and secondary education (teachers and students) and job rotation programmes and secondments to academia for existing work-force to access

unique QT infrastructure and expand knowledge base.
    - Develop and implement intense training programmes for Quantum Education (e.g. summer/winter schools)
- Raised quantum awareness across all members states in Europe through short-term, immediate actions to demonstrate societal benefits of QT.

After **six years** we will see

- Monitored the needs and challenges of QT education on the (i) tertiary and (ii) secondary education level and of (iii) the quantum industry and formulated measures for sustaining the efficient development (Education CSA).
- A pilot program to implement a reformed approach of both formal and informal QT learning in selected member states for the (i) secondary and (ii) tertiary education level and (iii) the quantum industry.
    - A certificate system in Quantum Technology based on empirically evaluated education standards.
    - Pan-European launch of interdisciplinary QT-Master courses in Quantum Engineering containing a component of leadership, industry and entrepreneurial skills training, based on the evaluation results of the pilot programme.
- Joint international graduate schools for learners from different areas with opportunity for students to gather international experience (Marie Curie ITN/ETN)
- Research-based quantum curricula recommendations and empirically evaluated teaching strategies for secondary schools
- University activities for high school students (Quantum Master Classes)
- Recommendations for education at primary level in preparation for QT education at secondary level
- Involvement of decision makers through e.g. educational advisory boards, job shadowing, grey literature/briefings/recommendations
- Network platform and regular international meetings systematically extended to SMEs
- Transcending support across all measures to address inclusiveness in terms of diversity in internal (e.g. gender, ethnicity), external (e.g. parental status, work experience) and organizational dimension (e.g. work location, seniority)[37] (included in the budget of the individual measure)
- Transcending support across all measures to reach out to broader communities (included in the budget of the individual measure)

After **ten years** we will have

- Monitored the needs and challenges of QT education on the (i) tertiary and (ii) secondary education level and of (iii) the quantum industry and formulated measures for sustaining the efficient development (Education CSA).
- established self-sustained pan-European education programmes in quantum technology
- implemented innovative research-based curricula on the secondary and tertiary level that will
    - include frontier science and real-life scientific challenges
    - build on a combination of formal, rigorous education in quantum science and technology and conceptual, intuition-based learning approaches
    - integrate school activities and extracurricular activities embedded in national initiatives (e.g. exhibitions, science festivals, student laboratories,…)
    - be tested and evaluated in real teaching situations in teachers' education

- supplied a quantum-ready workforce for a quantum industry

Conclusion

In summary, the creation of a learning ecosystem embracing the concepts of quantum physics at all levels ranging from school up to the working environment is required for the quantum ready workforce to emerge. The envisioned strategy is an educational approach based on a combination of conceptual understanding and formal training that starts with the societal and company needs and builds up into a quality controlled educational concept. This demonstrates the clear need for substantial investment and calls the EC to launch an urgent call for the Education Coordination and Support Action within H2020 and to allocate the budget for the calls dedicated to a quality controlled Quantum Technology oriented education program and for a persistent Education CSA within the next FP9.

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