Introducing Quantum Information and Computation to a Broader Audience with MOOCs at OpenHPI

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Abstract

Quantum computing is an exciting field with high disruptive potential, but very difficult to access. For this reason, numerous concepts are being developed worldwide on how quantum computing can be taught. This always raises questions about the didactic concept, the content actually taught, and how to measure the success of the teaching concept. In 2022 and 2023, the authors gave a total of nine two-week MOOCs (massive open online courses) with different possible learning paths on the Hasso Plattner Institute's OpenHPI platform. The platform's purpose is to make computer science education available to everyone free of charge. The nine quantum courses form a self-contained curriculum. A total of 17157 course attendances have been taken by 7413 natural persons, and the number is still rising. This paper presents the course concept and then evaluates the anonymized data on the background of the participants, their behavior in the courses, and their learning success. In the present paper for the first time such a large dataset of MOOC-based quantum computing education is analyzed. The summarized results are a heterogeneous personal background of the participants biased towards IT professionals, a majority following the didactic recommendations, and a high success rate, which is strongly correlatatd to following the didactic recommendations. The amount of data from such a large group of quantum computing learners offers numerous starting points for further research in the field of quantum computing education.

Keywords: Quantum computing, quantum information, quantum algorithms, education, MOOC (Massive Open Online Course), statistics, participant's behavior

1 Introduction

Quantum technologies are considered to be one of the most important technologies of the near future. Recently, the sub-area of quantum computing and quantum communication has increasingly come into focus, see section 2 for a brief glance at the literature. Many companies have launched initial innovation projects in order not to miss out on these technologies. However, a major problem is the lack of skilled workers, particularly in the field of quantum computing. Universities have now set up relevant courses, but the number of graduates will not meet the expected demand for specialists. Politicians have recognized this and have launched various programs. The Federal Ministry of Education and Research in Germany (BMBF) has therefore initiated the "Quantum Future of Education" funding measure for 2021. The aim was to "develop innovative, interdisciplinary concepts and programs for education and training in quantum technologies".

As part of this project, an innovative MOOC (Massive Open Online Courses) curriculum on topics related to quantum computing was developed by the authors of the present paper in cooperation with the Hasso Plattner Institute (HPI). The curriculum consists of nine courses and is explicitly addressed at an audience with little prior knowledge of the subject. The aim was to pick up participants at their level of knowledge and use innovative didactic concepts to convey a sound understanding of various areas of quantum computing. The focus was not on quantum physics or mathematics but on applications of the underlying concepts. As this was a BMBF project and was primarily aimed at a German audience, the MOOC content is in German with an ongoing process of English subtitles being added. The knowledge acquired in the MOOCs is intended to serve as a starting point for further individual specialized professional training.

To make it easier for participants to get started, they are offered various learning paths. This allowes participants to put together an individual learning profile depending on their previous knowledge and interests. Up to January 2024, more than 7413 participants attended the MOOCs. The topic of this paper is to analyze the learning behavior of these participants within the MOOCs. Therefore, the following research questions are addressed:

RQ 1: Did the MOOCs address a broader audience with different professional and personal characteristics?
RQ 2: Did the participants follow the given learning paths and other learning recommendations?

RQ 3: Were the desired competencies acquired by the participants in the courses, and did using the recommended learning items contribute to the learning success?

This paper is organized as follows. Section 2 provides a brief (and necessarily selective) overview of the enormous amount of literature on quantum computing education. Section 3 presents the didactic concept of the curriculum under consideration in this paper, as well as the course's contents. The content is also categorized with respect to the European Competence Framework for Quantum Technologies [1]. Section 4 evaluates the data collected by HPI during the courses with respect to the three research questions mentioned above. In Section 5, based on the results of section 4, we draw conclusions with respect to the research questions and point out topics for further research.

2 Literature Review

While quantum technologies have recently gained prominence in educational research, the investigation into quantum physics pedagogy is longstanding [2]. Bitzenbauer's literature review spanning 2000 to 2021 encapsulates 1520 works on this subject.

Research in imparting skills and competencies for quantum technologies has primarily centered on university education, particularly Bachelor's and Master's degree programs [3]. Aiello's work discusses 18 programs dedicated to training in quantum information science and engineering, emphasizing the necessity for corresponding investments across various stakeholders.

A targeted approach to teaching quantum technology and computing at US universities, especially within Historically Black Colleges and Universities (HBCUs), have been noted [4]. Lee's research addresses issues of Black representation and workforce diversity in quantum information science and engineering.

Bungum's study focuses on developing a quantum course for master's level information technology students, drawing insights from participant interviews [5]. Similarly, Stump's analysis explores student difficulties and misunderstandings regarding quantum topics [6].

An evaluation of interdisciplinary approaches to teaching quantum information science is detailed in Meyer's work, highlighting the influence of instructors and the need for diverse perspectives [7]. The presentation of a 1D quantum simulation and visualization tool by Zaman Ahmed aims to enhance understanding of quantum phenomena from the students' perspective [8].

Delgado's examination of the effects of the COVID-19 pandemic on quantum information science education underscores the evolving landscape of online teaching modalities [9]. Lastly, Hasanovic's account of the NSF-funded EdQuantum project highlights efforts to develop a curriculum for future quantum technicians [10].

In contrast to tertiary education, there has been a scant focus on elementary and secondary schools in the realm of educational research on quantum topics. Noteworthy among the few exceptions is the work by Bondani et al. [11]. This study is conducted within the European QTEdu CSA project, a component of the "Quantum Technologies" flagship, wherein courses on quantum physics and the application of quantum technologies are devised, implemented, and evaluated among approximately 250 students. Freericks et al. [12] already 2017 developed MOOCs for teaching quantum mechanics to over 28.000 non-scientists.

The training imparted in both school and university settings on quantum technologies ultimately aims to address the anticipated global demand for skilled professionals in these domains. This foreseen need is compellingly expounded upon by Venegas-Gomez and Plunkett [13, 14].

Several works specifically tackle the imperative of cultivating a requisite national and international workforce in quantum domains. Fox et al. [15] conclude that the commercialization of quantum technologies necessitates an adequately trained workforce, drawing insights from a qualitative study involving 21 US companies. Asfaw et al. [16] chart a roadmap for developing a commensurate workforce through the establishment of a quantum engineering education program, informed by a survey of 480 researchers across US universities, government agencies, industry, and research laboratories.

Although the aforementioned studies primarily center on the US landscape works such as those by Gerke et al. [17], Greinert et al. [1, 18], contribute to the formulation and presentation of a European competence framework. This framework underpins the development of training programs aimed at nurturing the future quantum workforce. Such initiatives are integral to the European Flagship project QTEdu, which seeks to establish a framework for second-generation quantum technologies.

The education and training of specialists in quantum technologies necessitate broader dissemination of these subjects in academic institutions alone. Engagement with individuals already employed in companies is imperative. Additionally, initiatives must cater to students and schoolchildren lacking adequate educational provisions thus far.

Quantum-related online courses were introduced at the European Research Center CERN in 2020, as evaluated in Combarro's report [19], which examines participant demographics and course outreach.

Maldonado-Romo's study reports on a Spanish-language quantum online event featuring introductory workshops and hackathons, engaging 220 participants from Latin America, with two-thirds being beginners [20].

The integrated approach presented in the present paper, which encompasses fundamental quantum concepts, quantum computing, and quantum cryptography, is echoed in Aithal's work [21]. Notably, Aithal underscores synergies among various topics within the realm of Information, Communication, and Computing Technologies (ICCT).

3 The OpenHPI Quantum Channel and the curriculum on Quantum Computing

Since 2012, the Hasso Plattner Institute (HPI) operates the online educational platform OpenHPI (https://open.hpi.de). The platform offers free access to MOOCs in the field of information technology. A MOOC at OpenHPI consists usually of around 20 concise videos (approximately 10-15 minutes each), 10 self-tests to assess participant learning progress, and one final examination test. Each course is conducted within a specified timeframe. Participants can repeat self-tests as needed, but the final exam can only be taken once online at the end of the time frame. The time frame is usually two weeks since studies in the literature supported the determination that a two-week module with integrated self-tests and a final exam is optimal [22].

Throughout the course's timeframe, participants can engage in discussions and pose questions within a forum moderated by the instructor. Answers to questions and comments are usually provided within one day. A course can be completed in two ways. If participants have accessed more than 50% of the items (videos, self-tests, additional material), they receive a certificate of attendance. If participants have more than 50% of the points achieved in the final examination, they receive a qualification certificate.

Even after the MOOCs have ended, the courses are still available to new interested parties. However, the forums are closed, and the final exam cannot be taken anymore. The videos can now be viewed on the platform without registering. However, registered participants can access the self-test and old forum entries. Participants can still complete the course successfully by accessing 50 % or more of the items. Then they will also receive a certificate of attendance.

In the present paper, a distinction between so-called course learners and self-learners is made. Course learners attend the course during the time-frame and are able to interact with the course instructor and fellow students. Self-learners register for the course after the ending of the time-frame. They can only attend the course in a non-interactive way.

In 2022, a dedicated channel for quantum computing was established on OpenHPI (https://open.hpi.de/channels/quantum). The channel features 15 MOOCs addressing various aspects of quantum computing. The kernel is a curriculum of nine interconnected and thematically coordinated modules, developed by the authors of the present paper from June 2022 to July 2023. They consist of three introduction courses, three courses about cryptography, and three courses about algorithms and programming. The last two courses, Algo 2 and Algo 3, were merged into one course for practical reasons. Concurrently, six additional quantum MOOCs were developed as specialized, independent courses. These courses cover diverse topics such as quantum computing for school pupils, a general introduction to Qiskit, or advanced topics like simulating quantum systems (Quantum Computing for Natural Sciences). The present paper discusses and evaluates the curriculum of the nine interconnected quantum MOOCs forming the kernel of the channel.

3.1 Didactic Concept

The didactic concept aimes to give participants with no prior knowledge of mathematics or physics a sound introduction to quantum information. The broad field is structured by self-contained learning paths so that participants can set their own priorities and not have to deal with topics outside their area of interest. In the end they are able to use the acquired knowledge to face the quantum computing topics occurring in their proper professional practice. This leads to a structure of nine courses. These courses are categorized into three sections: three introductory modules (Intro 1, Intro 2, and Intro 3), three modules focusing on quantum cryptography (Crypto 1, Crypto 2, and Crypto 3), and three modules on quantum algorithms (Algo 1, Algo

2, and Algo 3). The modular structure allows participants to customize their learning paths based on their interests and pre-existing knowledge. The learning paths are illustrated in figure 1.

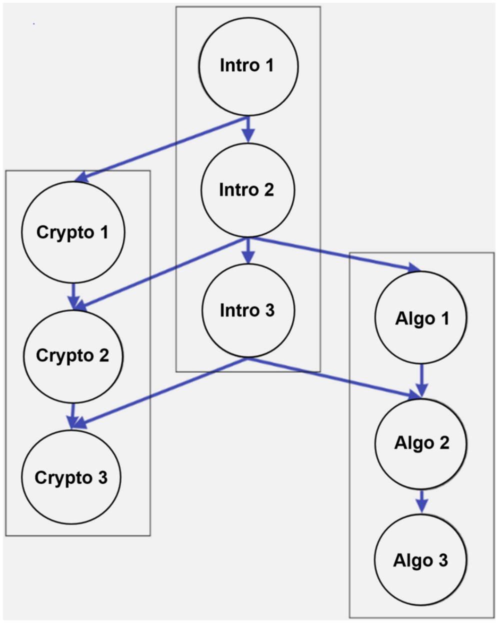


Fig. 1 Structure of the curriculum with nine courses and self-contained learning paths.

In designing the individual courses, the authors drew on their experience of teaching at Universities of Applied Sciences. The aim here is always to assume as little prior knowledge as possible, minimize the theoretical background, use graphical representations, and activate the participants through integrated exercises. Repetitions of the same topic in different courses from different perspectives are also intentionally included to deepen the participants' understanding.

In the introductory modules, the "quantum cube" is used throughout to illustrate quantum register states and the effect of quantum gates. This model was developed by Just [23, 24] and since then has been studied and used as an intuitive tool for visualizing quantum entanglement and quantum computation [25–27]. The quantum cube represents the state of an n-qubit register by providing one dimension in n-dimensional Euclidean space to each qubit. It then utilizes the standard n-dimensional cube with corners $(0, ..., 0)$ up to $(1, ..., 1)$. For a given register state, it places the amplitudes of the basis states (in any suitable representation of numbers, i.e. digits, arrows, squares, cubes or circles) at the corresponding corners of the n-dimensional cube. The application of quantum gates to a quantum register can then be visualized as a swapping, rotation, or mixing of the numbers at the corners of the cube. Especially for dimensions up to 4, quantum entanglement and quantum algorithms can be impressively demonstrated visually, without any prior knowledge of linear

algebra. The first two introductory courses use the quantum cube to illustrate simple quantum algorithms like the teleportation algorithm, which as was already published before. In the third introductory course, the cube model is applied for the first time to the advanced issues of quantum oracles and quantum phase kickback. This serves not only to make it easy to understand for the participants but also to demonstrate that the cube model can be applied for visualizing abstract algorithmic concepts [28]. The focus on quantum cryptography and quantum algorithms use Qiskit [29] to provide easy, hands-on access for the participants. The code is made available to the participants, so they can also experiment independently of the course.
The quantum cryptography series of modules largely dispenses with formal mathematical formulations and uses many examples to illustrate the concepts and mechanisms. For example, simulation examples and graphical diagrams demonstrate entanglement swapping and purification very well.
In the algorithmic course series, the focus is on the practical implementation and less on analytical investigations of the algorithms. Access to the quantum algorithms via programming has the advantage that complex calculations can be omitted and a strong emphasis can be placed on demonstrations.
In addition to the MOOCs, twenty participants were selected by the HPI to participate in a workshop associated with the courses. The workshop was guided by members of the HPI Academy and the authors of the present paper. It used the design thinking method (for further information see e.g. [30]) and aimed to develop tangible applications of quantum technologies. The workshop took the style of a business game. A fictitious company had to be made "quantum-ready" by the participants. There were no limits to the imagination. Since only a few selected participants could attend the workshop, its evaluation is not the topic of the present paper.

3.2 Module Content

The biggest challenge for the content design of the courses was the different and heterogeneous prior knowledge of the participants. As the courses are aimed at a broad audience, only minimal mathematical and physical knowledge could be required. On the other hand, the aim of the course series was for participants to have a deeper understanding and overview of current topics after successfully completing the curriculum. The bridge between minimal prior knowledge and deeper understanding at the end of the curriculum was built by choosing the contents of the courses as follows.

In the introductory module series, the first module (Intro 1) introduces logical qubits, the elementary gates X, Z, H, and CNOT, and the gate model for the description of algorithms. Since the cube model for illustration [23, 24] is used, this very quickly familiarized the participants with quantum phenomena known from the press such as superposition and entanglement. In the second course (Intro 2), the algorithm for teleportation is presented. Then elementary mathematical description tools ($2^n \times 2^n$-matrices, the operations of matrix multiplication and tensoring, and complex numbers) are introduced. Formal definitions are deliberately omitted. The focus is on examples and applications to give the participants an intuitive understanding of the concepts. The third module (Intro 3) deals with quantum oracles and the phenomenon of phase kickback, again taking advantage of the quantum cube for visualizing abstract algorithmic concepts. These two concepts form the basis of many classical quantum algorithms. A brief excursion into adiabatic quantum computing concludes the introductory module series.

In the module series on quantum cryptography, the first module (Crypto 1) explains elementary concepts from classical cryptography using examples. The somewhat inaccessible terms computationally secure and perfectly secure are also introduced. It is shown how quantum computers attack common asymmetric encryption methods. The BB84 key exchange protocol [31] is discussed in detail (including simple error correction and privacy amplification)) and its physical implementation and attack possibilities are explained. In the second module (Crypto 2) the central topic is the property of entangled quantum systems (in particular bipartite systems, Schmidt decomposition, partial trace) and the key exchange protocol derived from this. Instead of mathematical calculations, simulations with Qiskit [29] or quantum games (CHSH-Inequality) [32, 33] are used. The ideas on the security proofs of the protocols are also explained. The third module (Crypto 3) discusses the concept of a quantum internet and the associated technological challenges (repeaters and error correction).

In the first module of the series on quantum algorithms and programming (Algo 1), the implementation of the gate model with Qiskit [29] is presented. The classic quantum algorithms [34] such as teleportation, Deutsch's algorithm, Deutsch-Jozsa's algorithm, and Grover's algorithm are presented using Qiskit. The Qiskit code is made available to the participants so that they can try out the algorithms on their computers. In the second module (Algo 2), somewhat more sophisticated algorithms such as the quantum Fourier transform, the Shor algorithm [35] and the HHL algorithm [36] are explained step by step using example implementations. The third part (Algo 3) deals with current NISQ algorithms [37], which can also run on existing error-prone hardware. In addition to Monte Carlo simulations, VQE and QAOA for solving optimization problems and algorithms see e.g. [38].

3.3 Mapping to Quantum Competencies

The three tables 1, 2 and 3 show which course teaches which competence up to which level, with the domains of possible knowledge and skills taken from the European Competence Framework for Quantum Technologies [1].

It can be seen that the curriculum covers a wide range of quantum information technology skills, mostly at level A1 of the European Competence Framework, and sometimes at level A2. This is in line with the aim of not assuming any prior knowledge, while still enabling participants to deepen their knowledge according to their needs and prior knowledge.

Table 1 Competence category: Concepts and Foundation

	Intro 1	Intro 2	Intro 3	Crypto 1	Crypto 2	Crypto 3	Algo 1	Algo 2/3
Basic Quantum concepts								
Superposition, Interference	A1	–	–	A1	–	–	A1	–
Unitary time evolution, Schrödinger equation	–	A1	A1	–	–	–	A1	–
Quantum measurement								
Probabilistic nature of quantum physics	A1	–	–	A1	–	–	A1	–
No cloning theorem, etc.	–	–	–	A1	–	–	–	–
Two state systems								
State representation, visualisation	A1	A1	A2	A1	A2	–	A1	–
Pure and mixed quantum states	–	–	–	–	A1	–	–	–
Mathematical formalism and information theory								
Mathematical foundations								
Linear algebra, functional analysis	–	A1	–	A1	–	–	A1	–
State space, Dirac notations	A1	–	–	A1	A1	–	–	–

4 Evaluation of the data collected

To analyze the field of participants and the success of the courses, the anonymized participant data provided by HPI is used. These data consist of two types of data sets:

Dataset 1: Once registered at OpenHPI, a pseudo ID is assigned to each participant, which is the same for all courses attended. Now for each course enrolment, there is an automatically generated data record with the pseudo ID, the date of enrolment in the course, and information on the number of course items taken (i.e. videos, self-test, and final exam), the number of posts in the forum and the success in the final exam, if this was taken. Information on the age of the participant is also sometimes included if disclosed by the participant.
Dataset 2: In addition, when registering for a course, each participant is asked to take part in a questionnaire on their personal background. This includes questions about gender, current professional activity, and previous education. Participation in this survey is anonymous and voluntary.

Across all courses in the curriculum under consideration, there are till January 2024 a total of 17157 course attendances of 7413 distinct participants. Among those 6232 participants were already registered on OpenHPI; 1181 created a new account on the same day they enrolled in their first course.

4.1 RQ 1: Did the MOOCs address a broader audience with different professional and personal characteristics?

In this section, the personal and professional background of the participants is analyzed. The information provided voluntarily by the participants is used for this purpose. Thus, the information relates to about 5700 of 17147 registrations, and participants who attended several courses may have answered more than once. Nevertheless,

Table 2 Competence category: Quantum communication and networks

	Intro 1	Intro 2	Intro 3	Crypto 1	Crypto 2	Crypto 3	Algo 1	Algo 2/3
Basics								
Conventional and PQC, combined cryptographic approaches	–	–	–	A1	A1	–	–	–
Quantum teleportation, Bell state measurement	–	A1	–	–	A1	–	–	–
Security proof, side-channel-attacks	–	–	–	–	A1	–	–	–
Quantum random number generators								
Secure keys, e.g. for QKD	A1	–	–	A1	A1	–	–	–
Random numbers for algorithms, e.g. online gambling	A1	–	–	–	–	–	–	–
Quantum key distribution QKD								
QKD basic protocols, e.g. BB84, B92, E91	–	–	–	A1	A2	–	–	–
Measurement-device independent QKD and device independent QKD	–	–	–	–	A1	–	–	–
Quantum key management systems, QKD modules	–	–	–	–	–	A1	–	–
Applications of quantum cryptography								
Secure access to cloud-based quantum computing, delegated quantum computing	–	–	–	–	–	A1	–	–
Quantum internet								
Quantum network nodes, memories and switches	–	–	–	–	–	A1	–	–
Quantum repeaters, entanglement swapping, entanglement purification	–	–	–	–	A1	A1	–	–
Free-space communication	–	–	–	A1	–	–	–	–
Quantum internet applications)								
Full quantum communication network, QKD trusted node networks (secure data transfer)	–	–	–	–	–	A1	–	–

the analyses provide good indications of the spectrum of participants present and of frequently occurring characteristics.
The following criteria are analyzed:

- age (Dataset 1)
- gender (Dataset 2)
- status of employment (i.e. student, employee, pensioner) (Dataset 2)
- professional area (i.e. IT, administration, education) (Dataset 2)
- highest educational qualification (Dataset 2)

It turns out that the typical participant in a course is between 50 and 59 years old, male, employed in IT, and has a diploma or master's degree. These characteristics are mentioned in between 30% and 80% of registrations. But often there is a wide variety of answers for the non-typical participants. The courses were therefore also attended by hundreds to thousands of participants who are female, do not work in IT, or do not have a university degree.

Table 3 Competence category: Quantum Computing and Simulation

	Intro 1	Intro 2	Intro 3	Crypto 1	Crypto 2	Crypto 3	Algo 1	Algo 2/3
Basics								
Qubits, quantum gates, ...	A1	–	A2	–	–	–	A1	A2
Circuit design, notation, matrix representation	A1	A1	–	–	–	–	A1	A2
Basic quantum programming techniques	–	A1	–	–	–	–	A1	A2
Quantum simulators								
Quantum annealers	–	–	A1	–	–	–	–	–
Quantum programming tools , error correction								
Quantum assembler languages and software development kits, quantum circuit simulation	–	–	–	–	–	–	A1	A2
Quantum compilers,high-level programming with pre-defined subroutines	–	–	–	–	–	–	–	A2
Cloud platforms	–	–	–	–	–	–	A1	A2
Quantum error correction	–	–	–	–	–	A1	–	–
Quantum computing subroutines								
Quantum amplitude amplification	–	–	–	–	–	–	–	A2
QFT, hidden subgroup finding	–	–	–	–	–	–	–	A1
Quantum phase estimation	–	–	A1	–	–	–	–	A2
Quantum linear algebra subroutines, quantum singular value decomposition	–	–	–	–	–	–	–	A1
Quantum algorithms								
Numer theory and factorisation	–	–	–	–	–	–	–	A1
Oracular algorithms and database search	–	–	A1	–	–	–	A1	A2
Linear algebra (e.g. HHL-algorithm)	–	–	–	–	–	–	–	A1
Quantum optimisation	–	–	–	–	–	–	–	A1
Quantum machine learning, quantum neural networks	–	–	–	–	–	–	–	A1
Quantum simulation algorithms	–	–	–	–	–	–	–	A1
NISQ-Algorithms, VQE, QAOA	–	–	–	–	–	–	–	A1
Application of quantum computing								
Data security and cryptography	–	–	–	–	A1	A1	–	–

Figures (2) - (6) provide detailed information: In Figure (2) we show the distribution of age groups over all participants, without double countings of participants. Unfortunately, the majority (4747 participants) did not disclose their age. Of those who revealed their age, a majority of participants are in the 50-59 age group.

Figure (3) shows the distribution of genders. At over 80%, the proportion of men is even higher than is typically observed in STEM subjects, where the proportion of men is regularly around 2/3.

Figures (4) - (6) reveal information about professional characteristics. Over 60% of survey participants described their employment status as employed, followed by retired people (approx. 17%) and students at universities and others (approx. 7% each). Unsurprisingly, around 58% of participants categorize themselves in the IT sector, followed by other (around 16%), education (around 14%), and engineering (around 12%). However, it was also possible to reach people from administration and

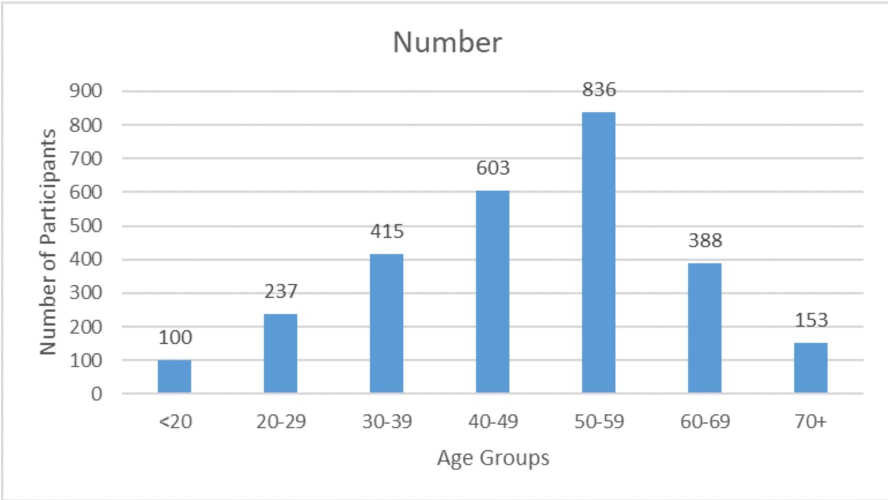


Fig. 2 Distribution of age groups over all participants. Participants in the survey: 2732

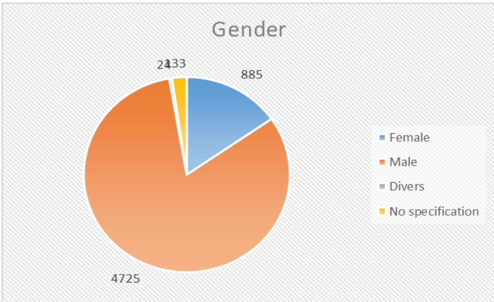


Fig. 3 Distribution of different genders. Registrations in the survey: 5767

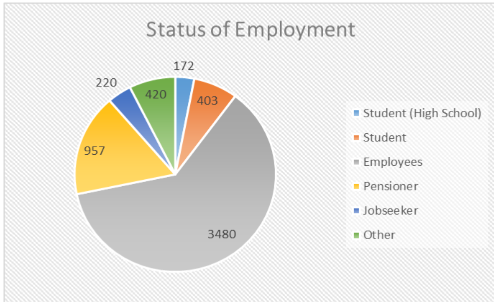
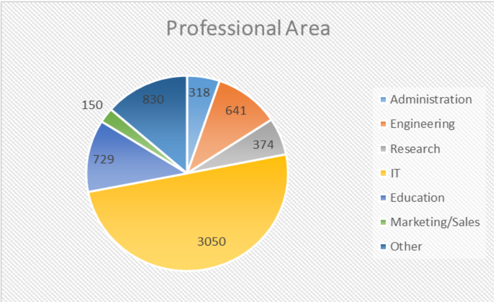


Fig. 4 Staus of Employment. Registrations in the survey: 5652

marketing/sales. In terms of professional qualifications, the MA degree dominates with approx. 54%, followed by a Bachelor's degree (approx. 18%) and a doctorate (approx. 17%). Around 15% of respondents stated that they had a non-academic professional qualification.

4.2 RQ 2: Did the participants follow given learning paths and other learning recommendations?

In this section, we look at the learning behavior of the participants. The data basis is the automatically generated, anonymized data records, i.e. there is a complete data basis without double counting (Dataset 1). A data record refers to one participant in a course, with each participant having an unchanging pseudo ID across all courses. The following criteria are analyzed:



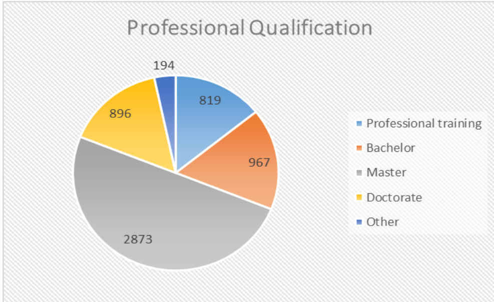


Fig. 5 Professional Area of the participants. Registrations in the survey: 5303

Fig. 6 Professionl qualification. Registrations in the survey: 5331

- Number of course registrations per participant
- Number of course registrations per course
- Items visited per participant and course
- Number of registrations per learning path

It turns out that many participants specifically selected one or a few courses and did not decide to complete the entire program with all the courses.

Among the courses, the number of enrolments for Intro 1 is the highest, followed by Intro 2, Crypto 1, and Algo1. The number of participants then decreases within the three areas. This order of enrolments also holds for the two subgroups here considered separately, namely enrolments during the course and enrolments for self-study after the course was finished.

When analyzing the items attended per course, after deducting the no-shows who were only enrolled and did not attend any items at all, the largest group of participants attended 75% to 100% of the items. The second largest group only attended less than 25% of the items. It turns out that only a small percentage of participants visited an average number of items between 26% and 75%.

When analyzing the learning paths, only participants who attended at least 25% of the items in the courses are considered, as only here can the effect of the didactic concept unfold. It turns out that the majority of these participants followed the recommended learning paths.

Figures (7) - (10) show the details. Figure (7) shows that many participants specifically selected one or a few courses and did not decide to complete the entire program with all courses. The number of participants attending one course, two courses, .., nine courses can be seen.

Figure (8) shows the registrations per course. Summed up over all nine courses, there are 17157 registrations until January 2024. 12468 are course learners and 4689 are self-learners. The courses continue to be open for self-learners, so the number of self-learners is still increasing.

Figure (9) displays for each course initially how many participants visited how many items. Participants are divided into 5 groups: the no-shows (participants who registered but did not visit any course item), and then the 4 groups of participants

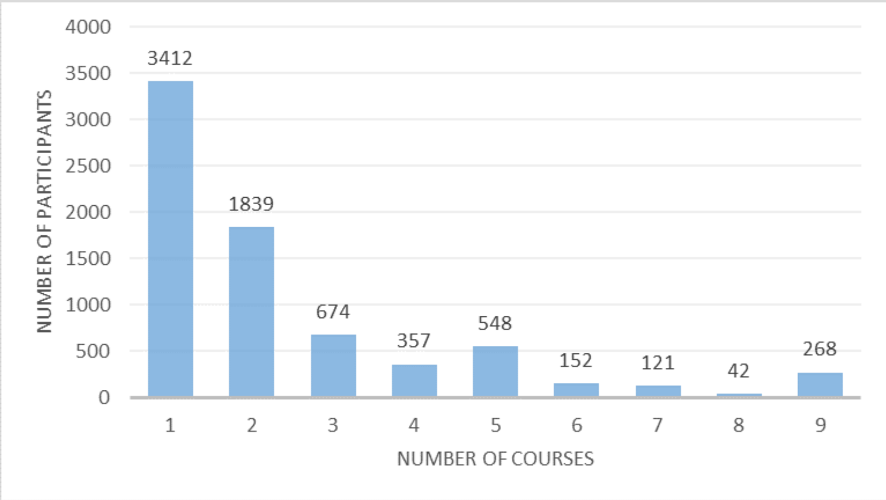


Fig. 7 Number of participants taken one, two, ..., nine courses.

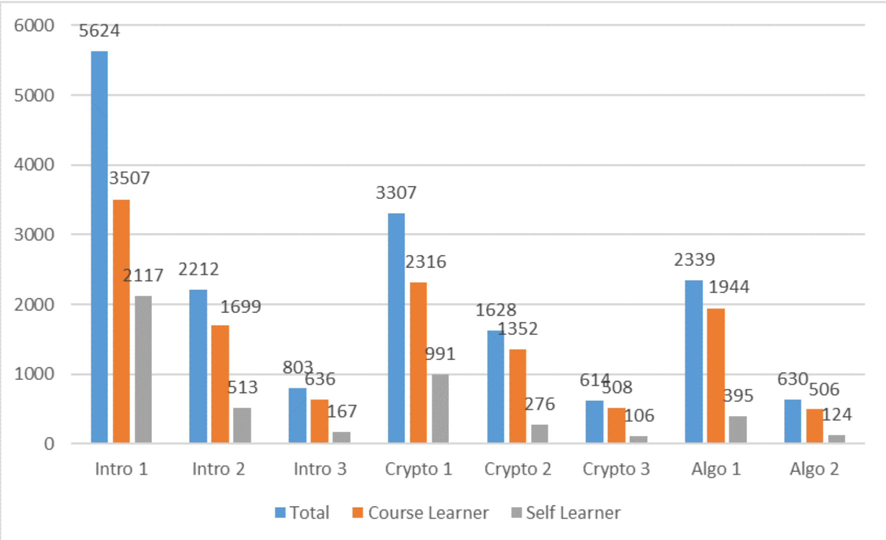


Fig. 8 Registrations per course, subdivided to course learners and self-lerners.

who visited between 1% and 25%, between 26% and 50%, between 51% and 75%, and more than 75% of the items. In all courses, the middle participant groups, those with shares between 26% and 75%, were by far the smallest groups. The other groups are roughly equal in size, with variations between individual courses.

Figure (10) shows which participants took which learning paths. Here, only course participations with at least 25% of visited items are considered, these are 2036 participants. The most visited learning path consists of the course Intro 1 only, with 720

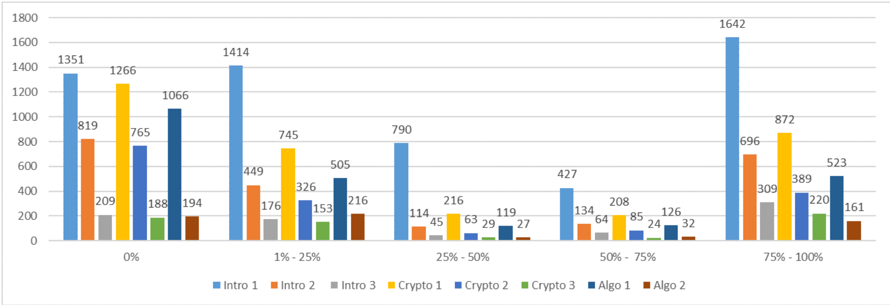


Fig. 9 Number of participants using percentage of the items.

participants. This is followed by the learning path Intro 1 and Crypto 1 with 316 participants, and then the learning path with all courses with 119 participants. Only in exceptional cases course selections outside of the recommended learning paths were made.

4.3 RQ 3: Were the desired competencies acquired by the course participants, and did using the recommended learning items contribute to the learning success?

To check the success of course participation, we split the 17157 data records into 12468 data records from course learners (CLs) and 4689 data records from self-learners (SLs). The distinction between course learners and self-learners was made in the data records based on the enrolment date for the course.

Course learners used the same learning items as self-learners, except that they also had the opportunity to exchange ideas and ask questions in the forum. They also took a final exam.

The learning success of course learners is derived from the result of the final examination. This is passed if 50% of the questions are answered correctly.
It can be seen that of the 12468 course learners, 4550 are no-shows, 3145 did not reach the 50% items threshold and 4773 successfully completed the course. This corresponds to 38% of all course learners.

Figure (11) shows the correlation between the learning success (proportion of the total score achieved including the final exam) and the proportion of the learning items attended. While only a few participants achieved a high overall score despite having attended fewer learning items, the majority showed a clear positive correlation between the two variables. A simple linear regression model of the score achieved with the explanatory variable proportion of items visited achieves an $R^2 = 0.27$. This underlines the significance of the learning materials visited for course success.

In Fig(13) we show that the mean of the number of items visited is significantly larger for the top performers of the courses (top 5%, top 10% and top 20% of the participants) compared with the remaining participants. Here "top$x$" means that a participant has achieved one of the x highest percentage results (i.e. the result of a top 5 performer is not necessarily better than that of 95% of the field of participants).

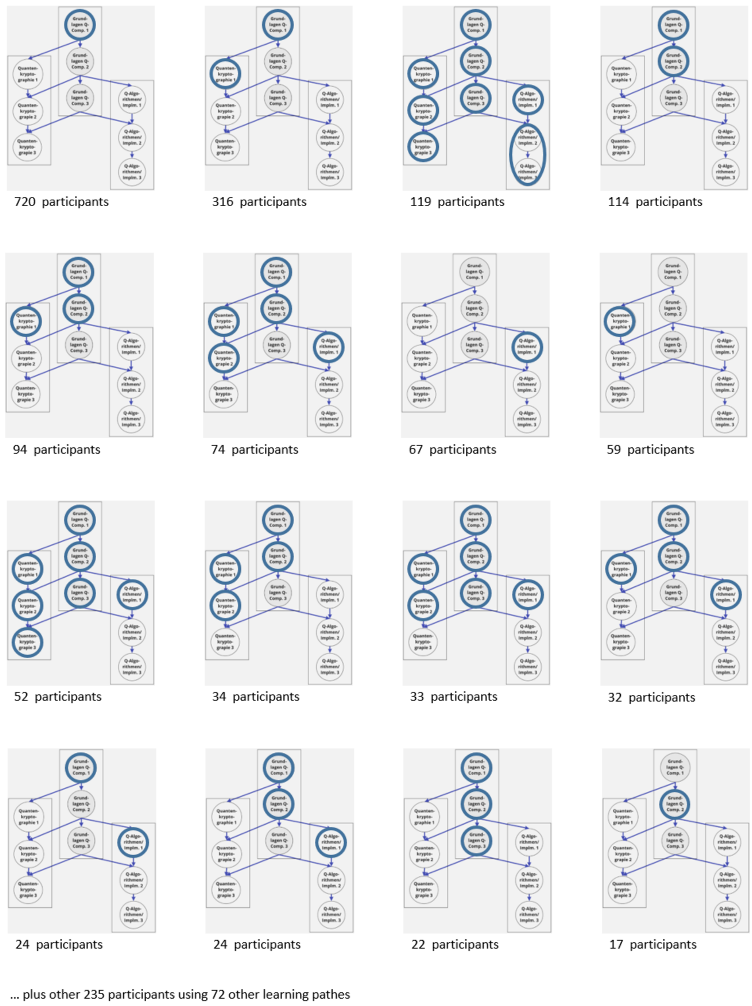


Fig. 10 The 16 most frequently used learning paths embedded to the untranslated German curriculum.

The top performers visited more than 92% of the items on average.

It can be seen that of the 4689 self-learners, 1369 were no-shows, 2181 did not visit 50% of the items and 1139 finished the course with success, so roughly a portion of 24% of the participants starting the course completed it with a certificate of attendance.

Fig(14) gives an overview and the details on course registrations for course learners and self-learners, the no-shows, the unsuccessful, and the successful participants. Across all courses and participants, 5912 completed the course; in 11245 cases the

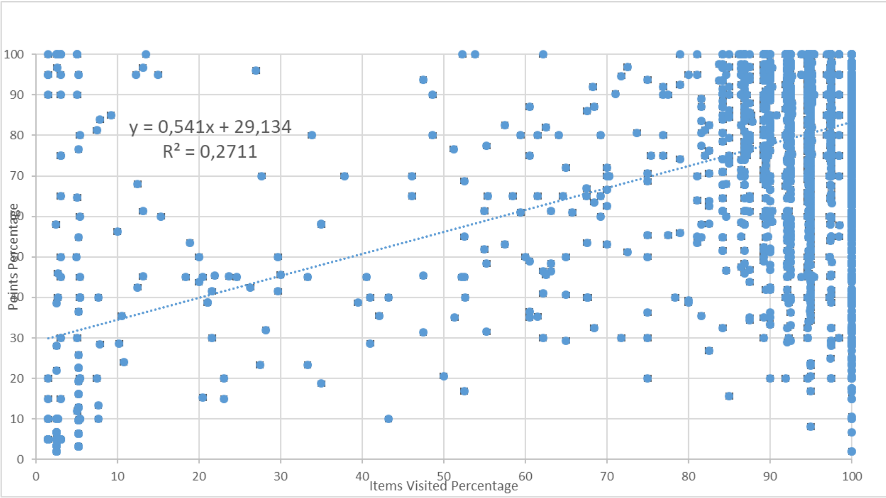


Fig. 11 Points percentage (=total score) of the course learners vs. percentage of items visited.

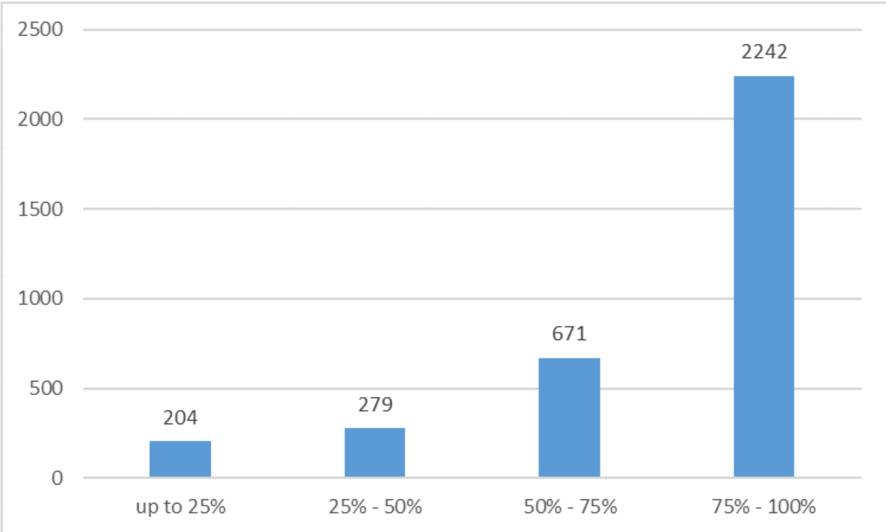


Fig. 12 Number of participants achieving points percentage of the final examination.

courses were not completed. It should be noted here that individual participants are counted separately in each course they attended.

5 Conclusions and topics for further research

In the previous section, we analyzed the participant's data and the data of their learning behavior in the core courses on quantum computing on the OpenHPI platform

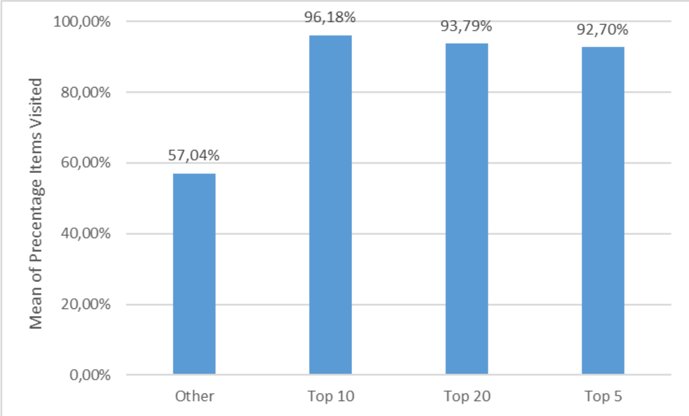


Fig. 13 Percentage of the items by Top Performers (Top 5, Top10, Top 20) and the other course-learners.

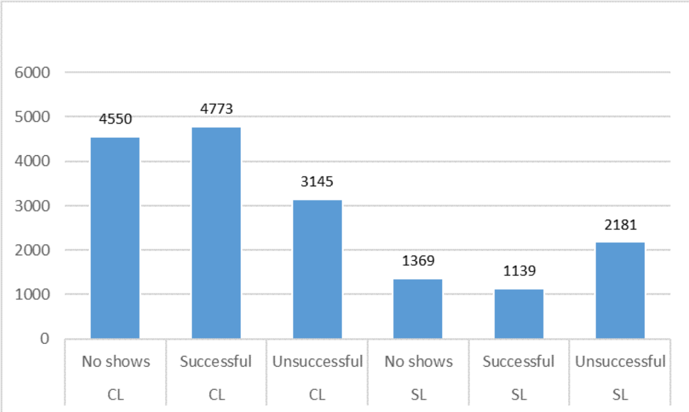


Fig. 14 Divided between course and self-learners the number of no-shows, unsuccessful, and successful participants are displayed.

that took place in the period from June 2022 to July 2023. This provides answers to the following research questions

RQ 1: Did the MOOCs address a broader audience with different professional and personal characteristics?
RQ 2: Did the participants follow the given learning paths and other learning recommendations?
RQ 3: Were the desired competencies acquired by the participants in the courses, and did using the recommended learning items contribute to the learning success?

It should be emphasized once again that all data included in the analyses is anonymized so that no conclusions can be drawn about individual participants.

RQ1: Our analyses show that a broad audience attended the quantum MOOCs. All age groups were represented, with the majority being over forty. Most participants had an IT background, but participants from non-technical professions are also a considerable part of the audience. The majority of participants has a university degree. As is often the case in technical and scientific fields, male participants also predominated in our courses. The analyses show that people not directly associated with a university are also interested in quantum computing. A broader audience with different professional and personal characteristics could therefore be addressed.

RQ2: As the field of quantum computing is very broad, various learning paths were suggested to the participants. With the MOOC platform's help, the participants' learning behavior could be tracked in detail. The analyses show that the recommended learning paths were often followed. Most participants attended an introductory course in each subject area (Intro 1, Crypto 1, Algo 1). Depending on their interests, they remained loyal to the topic and completed more advanced courses. A not inconsiderable number of participants also attended courses on several topics. More than 140 people completed all nine core MOOCs. The data shows that the recommenadtion of learning paths was highly accepted. Thus, there seems to be evidence that it is imporatant to suggest learning paths to participants for better orientation when dealing with complex topics.

RQ3: The generally recognized European Reference Framework for Quantum Technologies was used to select material. All content taught and tested in the examinations could be assigned to categories in the reference framework. Over 80% of exam participants passed the final exam, 50% even with a good to excellent result. It also shows that the success rate correlates with the number of learning materials consumed (videos, self-study tests, forum discussions). It can be stated that the learning elements provided by the MOOC platform are sufficient to teach participants the necessary skills.

In conclusion, one can say that the quantum MOOCs at OpenHPI were a big success and up to January 2024 reached more than 7400 participants from different age and professional groups. The MOOCs help to bring the topic of quantum computing closer to a broad audience outside of universities and research departments. Therefore, the topic has reached a broader audience.

In addition to the results discussed in the present paper, further research questions can be investigated based on the available data. It would be interesting to see, how exactly the participants worked with the video tutorials. For example, were the videos paused in between to better understand complicated details? Did the sometimes detailed discussions in the forum motivate the participants to engage with the topic? Another interesting question could deal with possible specific learning differences between male and female participants. More generally, the learning behavior of different subgroups could be analyzed in relation to age, professional situation, or educational attainment. Since the amount of data is large, the subgroups usually consist of hundreds of participants with respect to various characteristics, so that statistical analyses are meaningful.

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