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What do quantum computing students need to know about quantum physics?

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Abstract

Quantum computing is a rapidly developing technology, and we are experiencing an urgent need for experts in the field. However, there is a lack of traditions, research, and development on to what extent, and how, information technology students without a background in physics should be taught quantum physics. This paper contributes to the field by suggesting key topics in a course for information technology students on the master's level. We have identified a core content of eight key topics, ranging from content purely from quantum physics and the formalism of quantum mechanics to its use in quantum algorithms and coding. The proposed content forms part of a master's course developed for information technology students at Oslo Metropolitan University, Norway. By means of group interviews and questionnaires to students, the students' experiences of the course are investigated. Results indicate that information technology students are capable, and interested in, learning quantum physics for the purpose of education in quantum computing. An integrated approach, where students learn quantum physics and quantum computing in the same course is found to work well for most students. However, as the challenge is extensive for some, it is important to make the purpose of each component of the content clear.

Introduction

With the rapidly developing field of quantum computing and related technologies, there is an urgent need for educating computer scientist with expertise in this field [1-6]. Therefore, for example the EU initiative "The Quantum Flagship" is currently developing qualification profiles in quantum technologies and various target groups [7]. These profiles include concepts of quantum physics and physical foundations of quantum technologies alongside the more technological aspects of the field. However, little work has been undertaken to identify the concrete content of quantum physics that should be represented in the education of quantum computing experts [2], and how students in the target groups respond to this content. Traditionally, quantum physics has been taught exclusively to physics students in universities after they, in addition to mathematics, have studied mechanics, electromagnetism and other fields of classical physics. Johansson et al. [8] describe how the teaching of quantum physics typically is flavoured with a "shut up and calculate" discourse, emphasizing the mathematical formalism rather than interpretations, philosophical aspects, or technical applications. Research shows that quantum physics involves high learning demands for physics students- in terms of mastering the mathematical tools as well as conceptual understanding [9].Therefore it also challenges teachers and curriculum designers on how to support students' learning in quantum physics [e. g. 10, 11, 12]. These challenges are fortified as the current technological development in quantum computing brings a new target group to the scene, namely students in information technology. These students may have a reasonably strong background in mathematics but usually a rather weak background in physics.

This paper contributes to the field by suggesting a core content of quantum physics for information technology students specializing in quantum computing. It follows the ideas of educational reconstruction [13], which means reconstructing a knowledge field for educational purposes by identifying the general ideas it represents and its significance for the students' actual and future lives, in this case to learn and apply quantum computing in their work as computer scientists. Comparable developments are presented by Westfall and Leider [2] and by Fox, Zwickl and Lewandowski [3]. While the former has a strong focus on tools from linear algebra, the latter is somewhat dominated by computational techniques. In a wider scope, Asfaw et al. propose an extensive roadmap for building an education program for engineers in quantum information science and techonlogy [5].

Quantum computing, as it stands now, is indeed comprised of series of multiplications of two-by-two matrices and two-component complex vectors – or Kronecker products and tensor products thereof, respectively. In a technical sense, it is simply applied linear algebra. However, the foundation for quantum computing is quantum *physics,* and each aspect that provides quantum computing with any advantage over classical computing corresponds directly to phenomena specific to quantum physics. Thus, in the present study we also explore how a course on quantum computing for information technology students may also contain essential principles of quantum physics – and how it is used in quantum computing. Moreover, we present and discuss an empirical study of students' responses to the suggested course content in a course on quantum computing for master students in information technology at Oslo Metropolitan University in Norway.

A master's course on Quantum Information Technology

At Oslo Metropolitan University, a master's course on *Quantum Information Technology* is developed as a specialization course of 10 ects. The course is a mandatory part of the specialization in *Mathematical Modelling and Scientific Computing* within the international master's degree program *Applied Computer and Information Technology.* The main goal of the course is to equip students with the necessary knowledge and skills to work with quantum computing.

The course is designed with an integrated approach where quantum physics is taught as part of the course in information technology, not as a separate course. Practical implementations are key elements of the course, involving classical simulation of quantum physics as well as quantum programming.

Identifying key content of quantum physics for quantum information technology

The advantage that quantum computing has over classical computing rests mainly on two interrelated phenomena. The quantum information content, which is comprised by a set of two-level systems, *qubits*, is doubled each time a qubit is added to the system. In other words, the information content grows exponentially with the number of qubits. This, in turn, is related to the fact that the information is not necessarily a simple sequence of 0-s and 1-s, as is the case in a classical computer; it may in fact be a mixture, a linear combination, of all such sequences. With an initial system consisting of such a linear combination, all sequences of 0-s and 1-s are processes in parallel – in one single computation. This is referred to as *quantum parallelism*.

Unfortunately, this advantage may not be harnessed in a straight-forward manner due to the so-called *collapse of the wave function*. In a calculation, only one result may be read off, and the read-off is random. When quantum computing may still be advantageous over classical computing for certain applications, this rests on the fact that it is *coherent*; various components may either reinforce of cancel each other – like waves interfering. Present day quantum computers struggle to maintain this property over time, they are subject to *decoherence*. This, in turn, poses constraints on which quantum algorithms may fruitfully be implemented.

For an introduction to the key concepts of quantum computing, we refer the reader to, e.g., [14].

As the key content, we have identified eight topics in quantum physics and quantum computing. We present these topics with particular emphasis on the relation between the two:

1. **The wave function**: For a quantum system, all accessible information is contained in its *wave function*. We study how it provides information in a probabilistic manner, and how it collapses upon measurement. We also address how its complexity grows exponentially with the number of constituent particles.

2. **The dynamics of a moving wave function**: By numerically solving the time-dependent Schrödinger equation, which governs the evolution of a quantum system, the students experience how a wave function evolves for simple systems. Simulations involve phenomena such as *interference* and *tunnelling*. As mentioned, the fact that quantum states may be added coherently, thus allowing for interference, is fundamental to quantum computing as it, e.g., allows incorrect or undesired results to be cancelled and correct ones to be reinforced.

3. **Quantization**: From the time-independent Schrödinger equation it is seen how the energy of a particle confined in space may only assume one out of a discrete set of values. The notion of qubits rests on the fact that quantum systems may be quantized. We also revise how to estimate the ground state energy via the *variational principle* as a minimization problem.

4. **Entanglement**: A system consisting of two or more particles may feature global characteristics beyond what is known about each of the particles separately. This notion, which has no classical analogue, comes about via linear combinations as mentioned above. Quantum schemes such as *superdense coding* and *quantum teleportation* make direct use of

maximally entangled two-qubit states (*Bell states*). In this context, spin ½-particles serve particularly well as examples illustrating how qubits can be implemented and manipulated.

5. **Specific quantum algorithms**: To illustrate how quantum computing may be advantageous or superior to classical computing, specific quantum algorithms are reviewed. This includes *superdense coding*, the *Deutsch-Jozsa algorithm*, the *quantum fast Fourier transform* and *Grover's search algorithm*. While the most prominent quantum algorithm, *Shor's factorization algorithm*, could also be addressed, this may be somewhat involved technically for students with limited background in mathematics.

6. **Universal gates and approximations thereof**: Quantum algorithms such as the ones mentioned above may be implemented by constructing programs, or *circuits*, consisting of a sequence of *quantum gates* which typically operate on one or two qubits at a time. Such gates are determined by the Schrödinger equation. A universal set of gates is one that may be used to construct *any* quantum program. The students are to implement examples of quantum programs themselves on quantum emulators or actual quantum computers.

7. **Quantum solutions to optimization problems**: We explain how optimization problems may be tackled efficiently by the method of *quantum annealing*. This scheme relates to both the variational principle and quantum tunnelling. We also explain how such approaches differ from schemes in which quantum programs/circuits are built up from smaller gates as addressed above. A disadvantage of quantum annealers is that their applicability is limited to optimization problems. On the other hand, they have the advantage of being more robust against noise and decoherence.

8. **Noisy Intermediate Scale Quantum computing**: Present day quantum computers are quite far from the ideal ones in which a large number of qubits can be manipulated by imposing several quantum gates. Both these numbers are quite limited – for several reasons, one of them being *decoherence*. Despite such restrictions, we do expect to see practical applications of quantum computing in the near future.

The topics introduce several notions which differ quite a bit from prior intuition – both when it comes to quantum physics and quantum computing. Accordingly, the students' curiosity should be met and appreciated. This would mean that emerging discussion among students should be allowed to evolve, also when they deviate from the planned scope of the learning session. Moreover, due to this non-intuitive nature, efforts should be made to try and make the subjects as tangible as possible. Time is spent discussing fundamental experiments such as the double slit experiment with particles and the Stern-Gerlach experiment. Moreover, the nature of measurement and collapse of the wave function is studied by watching light passing through layers of polarization filters at various angles.

The real-life implementation of quantum programming is emphasized and enabled by the IBM Quantum platform, which allows for access to quantum computers with up to five qubits. In addition to implementing some standard, simple quantum schemes, students are also encouraged to devise their own quantum programs.

The empirical study: Research methods

The course with the described content was run autumn 2021 with 9 finishing students. Empirical data were collected through two digital questionnaires and two group interviews with students participating in the course. The study was undertaken with informed consent from the participating students and approved by the Norwegian centre for research data (NSD).

Students responded to the questionnaires in the beginning and towards the end of the semester. The questionnaires combined 5-points Likert scale questions with open questions. The first questionnaire had questions about students' interest in the various parts of the course, how strong background they perceived to have in the key content, and what they saw as main characteristics of quantum physics and quantum computing. The second questionnaire investigated how students perceived their learning gains in the same topics.

Five students participated in the first group interview, and two of the same students in the second interview. The interviews were undertaken by an external researcher not involved in the teaching of the course, students were ensured that their participation and expressed opinions had no influence on their grades. Both interviews lasted about 45 minutes.

Analysis of interview data followed approximately the steps described for thematic analysis by Braun and Clarke [15]. Codes were created partly deductively based on the interview guide and partly inductively from interview data. The result section of this paper is organized in terms of the set of codes developed.

Empirical results

We here firstly report some overall results from the two questionnaire surveys. Thereafter, interview results regarding students' experience of the course are presented, structured by the categories that emerged from analysis of interview data. The two students that participated in the second interview are labelled Student A and Student B, while individual students in the first interview are not labelled, i.e., they are all referred to as "Student".

Survey results: Students' interest in and familiarity with quantum physics and quantum computing

Results of selected items from the questionnaire, showing the students' responses to the two questions about their familiarity with topics and interests in various aspects of quantum computing are presented in Figure 1 and 2. Since the number of students in the course is low, care should be taken in interpreting these results since each individual has a large impact on the overall results. Still, Figure 1, shows a clear over-all increase in familiarity with the topics in question during the course. Beyond this, the students' responses do not reveal any particular tendency discriminating between the concepts.

Figure 2, on the other hand, is more informative in this regard. The students were presented with a list of potential reasons for taking an interest in the course and rate to what extent their own interests complied with these. Their answers would be one of the five alternatives *I strongly disagree*, *I disagree moderately*, *I am neutral*, *I agree moderately* or *I strongly agree*, which in Figure 2 has been converted to integers ranging from -2 to +2. In this case we see a general decline in the students' interest. It should be noted that since the scale actually ranges from -2 to 2, not 0 to 2, the reduction is not as severe as the graphics would suggest; the average responses do remain positive.

The over-all reduction in interest could, possibly, be explained by the students' acquiring a more realistic view on these topics.

It is interesting to note that at the end of the course, the distribution appears a lot more uniform than initially. Prior to the course, topics related specifically to technology and computation stood out from the other ones as more interesting for the students. This change could suggest that the introduction of the more theoretical topics has spurred the students' interest in these – relative to the other topics.

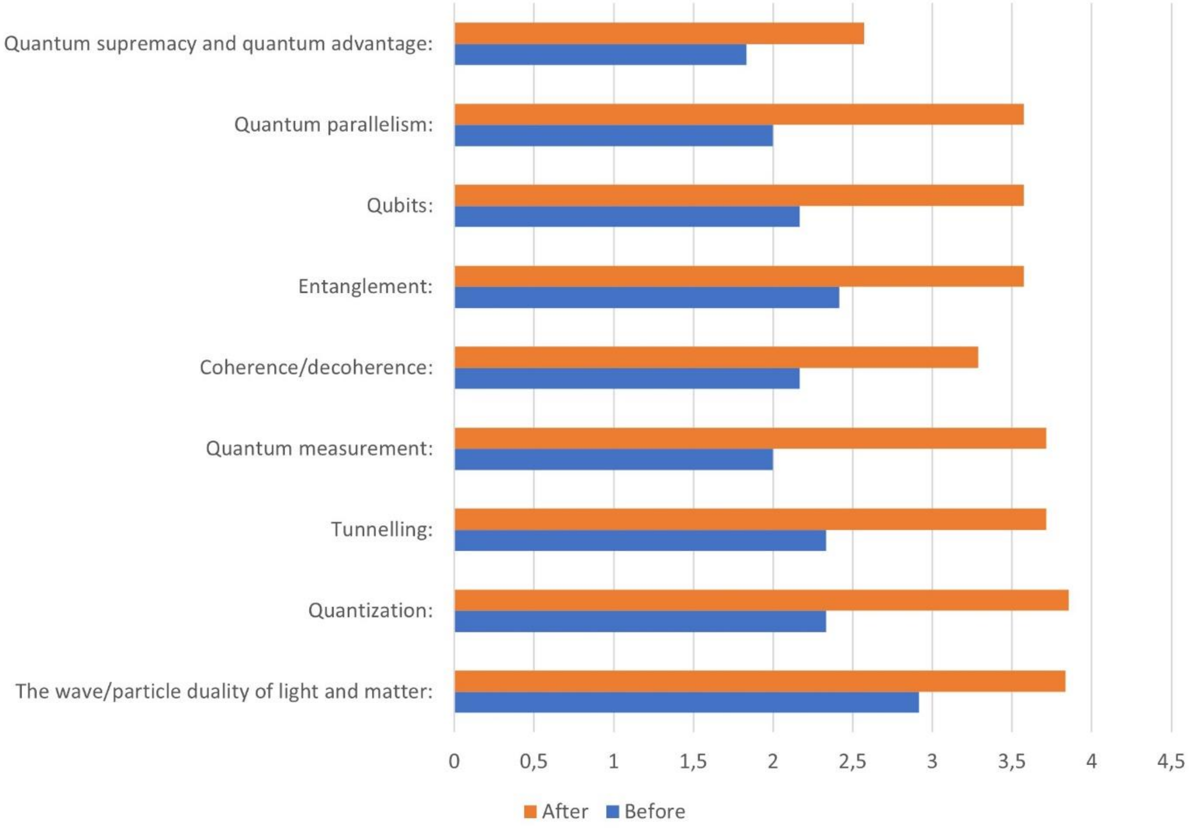

Figure 1: Both at the very beginning and at the end of the course, the students were asked to range their familiarity with several concepts pertaining ot quantum computing and quantum physics. The scale ranged from 1 to 5, and the chart displays the mean values.

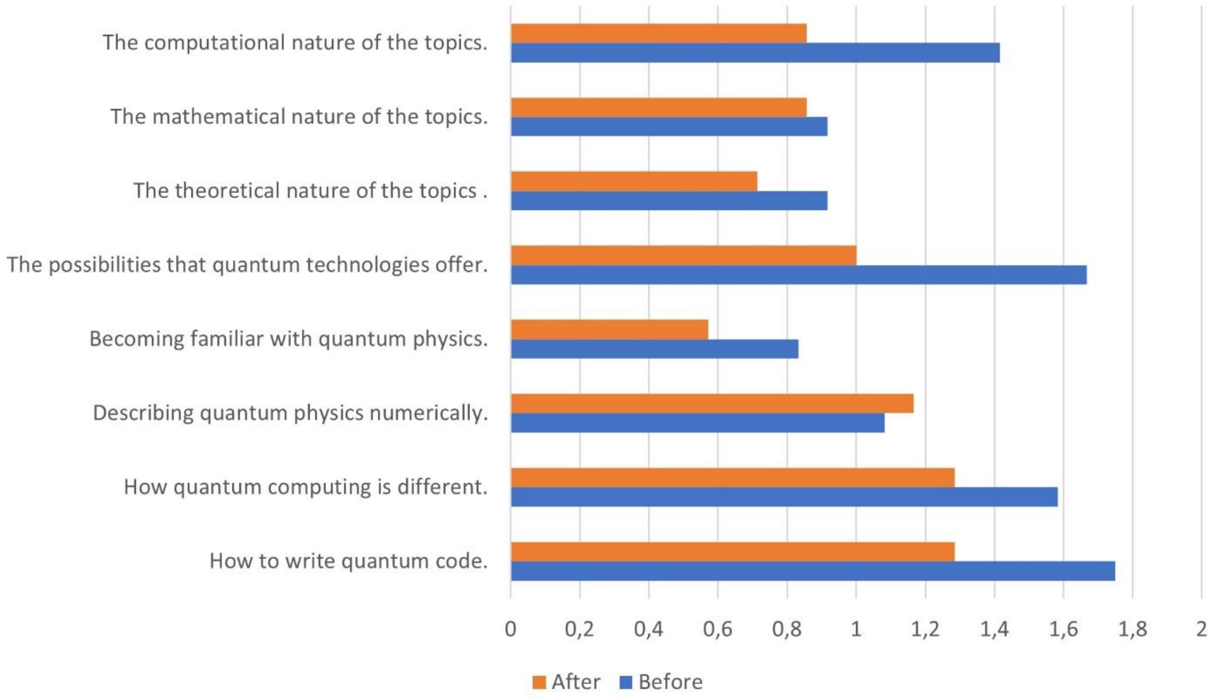

Figure 2: The students were presented with a list of possible reasons for taking in an interest in the course and asked to rate to what extent they comply. The scale ranges from disagreeing strongly, -2, to strong agreement, +2.

Responses to open questions in the first questionnaire in the beginning of the course revealed a large variation in the students' background knowledge of quantum physics and its role in quantum computing. Several students associated quantum physics with how things behave on subatomic scale, and some reported uncertainty and even a complete lack of understanding about what quantum physics is about, for example:

> *I'm not completely sure what quantum physics are, but I think it regards elementary particles, and how they interact in large "groups".*

and

> *I think it has to do with how many computations is being performed, quantum is many.*

Others showed quite informed insights in what quantum physics is, for example:

> *The ordinary physics are deterministic while the quantum physics are probabilistic. Therefore, in the quantum world concepts like superposition and entanglement occur, and the reality does not follow our intuition anymore. Everything is probable till the moment we measure it. As Einstein mentioned to Niels Bohr (father of quantum physics): "does it mean that the moon does not exist if we do not look at it"?*

This student pinpoints some of the main philosophical dilemmas that quantum physics has brought to stage, and the controversies about how it should be interpreted.

Interview results: Students' experiences of learning quantum physics

We here present the information technology students' experiences with learning quantum physics in the master's course as they emerged from the interviews, structured by the codes resulting from the thematic analysis.

"Scary but cool"

The students' motivation for a broad range of topics within quantum computing exposed in the questionnaire results was confirmed in the first group interview. Students here described their view of learning quantum physics as *cool*, *fascinating* and *interesting*. The interview revealed, however, that students had somewhat mixed feelings about learning quantum physics at the outset of the course. One student, who had previously learnt some quantum physics at upper secondary school, expressed that *"to be honest, I did not remember anything, and I was frightened!"*. This student found, however, that already early in the course s/he was able to master it. Another student expressed the mixed feelings towards quantum physics this way: *"It is scary, but it is cool, students on master level want that, it should be a bit scary"*. This indicates an attitude that master students acknowledge challenges and that the difficulties in themselves are motivating.

"Quantum physics is insane!"

The group of students expressed a combination of fascination and frustration with how quantum physics breaks with classical physics and our experiences of the physical world. For example, students expressed that: "*compared to classical physics, it is totally insane!*" and "*for me, the classical one is really intuitive, you have it in your life, you have seen it, but for the quantum you have just to accept!*". Some students were already in the first interview also able to articulate what this break with classical physics entails:

> *When you start learning quantum physics, you can forget [what you have previously learnt]! All of these rules do not apply! No determinism, it is all probabilistic."*

In the second interview, Student A explained what the probability in quantum physics means it this way:

> *It means that the behaviour of the system is uncertain by nature, it is actually random. Like when you flip a coin, it is random for us because we are never able to flip it with the same initial conditions every time, so it seems random because it is very tiny variations. But in quantum physics, it is actually random.*

The student's description of a system being uncertain by nature indicates a deep understanding of how quantum physics breaks with classical physics.

Although not being designed primarily to do so, the interviews also revealed some misconceptions. In the second interview, student B described the difference between quantum physics and classical physics in terms of quantum measurement:

> Student B: *Measurement in quantum space is totally different from the classical measurement, it is, you know, when you measure in a classical way, you measure, ok, you have the data. But when you measure in quantum space, you destroy it!*
>
> Interviewer: *That's interesting! Can you explain it?*

> Student B: *Nobody can explain it! It is physics behind this. Because we use entanglements, if you measure it, then you destroy the entangled qubits. The whole wave equation is destroyed after measurement, so... It is the physics behind it, I think!*

The student here appears to firstly mix up entanglement with superposition and secondly struggle with conceptualizing what the collapse of the wave function means, and what it is that thereby is “destroyed”. He therefore has severe problems in making sense of the use of quantum physics in quantum computing.

Mathematics as a tool for understanding

The students mainly point to conceptual understanding as the main challenge in the course. The mathematics involved seems to be less of a problem for the quantum computing students, and one of them even points to mathematics as a tool that helps to better understand the conceptual content of quantum theory:

> Student A: *I think it is great fun to see for example entanglement, which is very difficult to understand when one tries to explain what it is, but when you see it mathematically, you see that «Oh yes, mathematically this make very much sense!». But trying to imagine a particle that is connected to another particle and all that stuff…*
>
> *(…)*
>
> *The mathematics is very clear and easy to understand, it is not difficult mathematics as such, it is mostly linear algebra. But trying to grasp in more concrete terms what this means physically, that a particle can be several places simultaneously, superposition, what you call it, trying to understand it intuitively, is very hard, I think.*

This indicates that the strong background some information technology students have in mathematics, notably linear algebra, may provide for working with the formalism and conceptual challenges in parallel, and that the two may strengthen each other as described by student A above.

Students’ experience of the integrated approach

The integrated approach in the course, where learning of quantum physics is integrated with computer exercises and the necessary mathematical tools, meets varied reactions from the students. Some acknowledge the combination, while it might also confuse some students. Students A and B are representatives for these two viewpoints. In the interview, student A emphasize the importance to “test things” and see how things work:

> Student A: *It is important to see things, to test things, to go to the computer and see how things work. Because it is so difficult to understand. For me, it is important to check, did I understand this correctly, not understand it in a way where I can comprehend what is happening but to get an idea of these concepts. Visualize it or make it more tangible is good. For me it is also nice to see some of the maths, since the math is not so hard, so it is easy to see that the math makes sense. And then you try to apply it to physical objects and then it is really weird. To combine the things you can experience, the theory and the math, I like that.*

Student B, who struggles more to grasp the content of the course, uphold that the course was too crowded with very different content, and he has problems seeing what it was really about:

> Student B: *That was one course in one semester, and it wasn't quite clear, what is the purpose? Is it quantum physics? Is it quantum computing? Is it programming? Is it low level language learning? Is it about computing instruction? What is it about?*

For the physics content, Student B continues:

> Student B: *For the physics part, I would say, for just one course, it wasn't enough, but at the same time it was necessary, if for example we could have more courses, not just this one, that would be better, because we have just scratched the surface of everything. We couldn't go... there wasn't enough time to go deep into each topic.*

Following this sequence, the student supports the idea of rather learning the quantum physics in a separate course before the computing part, as this would make it clearer what to focus on. It is noteworthy, however, that even this student does not suggest removing the quantum physics part from the study program. This is in line with the questionnaire results, where none of the students suggested to completely eliminate quantum *physics* from the course.

The usefulness of learning quantum physics

When asked in the interview what they feel they need to know from quantum physics in order to do quantum computing, the students expressed that a basis of understanding is essential. They mostly relate this to the learning process, for example:

> *Learning more about the physics behind makes it easier to swallow all these ideas that quantum computing is using to do calculations we are using and all the algorithms we are looking at.*

and

> *You need to know a bit of quantum physics to not be overwhelmed by confusion.*

One student does, however, state that the quantum physics knowledge is not necessary from an application perspective:

> *It depends. If you are planning to get involved with hardware, to build a quantum computer… But from an application perspective, you just follow the rules!*

To *"follow the rules"* here indicates that it is possible to apply the mathematical procedures in quantum computing without knowing much about quantum physics, corresponding to a "shut up and code" version of the "shut up and calculate" stereotype for physics students. A related, but more sophisticated point comes up from student A in the second interview. This student points to the fact that quantum computing is still a very young field of expertise. Just like computer scientists in earlier years needed detailed understanding of transistors and how they operated, today's quantum programmers need a good grasp of quantum physics. The student continues:

> Student A: *That's where we are now, with the quantum computing, we need to understand, how do these qubits behave, to get good results. But this technology progresses, and also when... you don't really have to bother about superposition states, to know what that is, or*

> *entanglement, to do calculations, what you do, you just import your library, in Python or whatever, and then you just say: I want to run this type of algorithm, then you put in your parameters for your problem, you click on «run», and everything is set up automatically, as it is with classical computers these days. (…) As today I think it would be difficult, at least very confusing, to start programming quantum circuits without any quantum physics knowledge.*

The student's reasoning here demonstrates a good insight in the role of quantum physics in quantum computing and a mature perspective of this field of expertise and its development.

Discussion and conclusion

This paper has suggested a core content of quantum physics for students of quantum computing in higher education in terms of eight key topics, ranging from purely quantum physics concepts such as the wave function and quantization to specific quantum algorithms. This core content differs from quantum physics for secondary physics students in containing far more mathematical formalism, and from the teaching of quantum physics to university physics student by containing direct implementation rather than a wider range of physics examples and phenomena. The suggested content relies on the idea that familiarity with basic principles of quantum physics is constructive for students to understand, make use of and contribute to the development of quantum computing.

Prior to the course, results showed a wide variety of prior knowledge and preconceptions even if the sample was small. While some student responses exposed virtually no familiarity with quantum phenomena or so mistaken ideas that they cannot even be analysed in terms of well-known misconceptions, others could give rather insightful descriptions. The results also showed that the students were motivated for learning quantum physics, and that they after the course seemed to have a broader interest profile than before. Students reported, however, also mixed feeling towards quantum physics, represented by the expression *"scary but cool*", that directly resembles *"frightful but fun"* that has been used to label upper secondary physics students' attitude to physics [16].

Overall, the results indicate that it is feasible to present students in information technology with quantum physics beyond the mathematical tools from linear algebra and computational techniques. Interestingly, the information technology students appear to share the conceptual problems and challenges in interpreting the counterintuitive quantum physics phenomena and concepts described in physics education research [11], but do not describe the mathematical formalism as any challenge. On the contrary, the mathematics is actually described as a tool that enhances understanding of the conceptual content. This view is in contrast to how physics students often struggle to handle the mathematical formalism, and how this in turn may reinforce a *"shut up and calculate"* culture in quantum physics teaching for university students in physics [8]. A corresponding *"shut up and code"* attitude was not found among the students in the present study.

The integrated approach appears to have been useful for students, and the direct implementing of the content seems to contribute to their motivation. However, some students may struggle with seeing the purpose of the combined course content, indicating that it may create a high cognitive load. This is similar to what is also a dilemma in the inclusion of programming in physics instruction [17], as it requires learning the tools and the content simultaneously. Rather than eliminating the physics content or teaching quantum physics ahead of quantum computing for information technology students, we recommend making purposes of an integrated approach explicitly clear to students, to motivate them for the challenges and to give priority to guiding the students' own problem solving. This way, the fascinating world of quantum physics can be made available to information technology students who will use it to contribute to the development of tomorrow's technology.

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