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Teaching quantum computing to a group of students with diverse backgrounds

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Background

This study is concerned with the 7.5 ECTS Bachelor course Introduction to Quantum Computing which was offered at the KU at the Department for Mathematical Sciences in Block 4 2020 (See course description in appendix A). It was the first installment of such a course at KU and aside from the course description and intended learning outcomes (ILOs), which I inherited from a colleague; I was free to structure and develop the course and its progression self-dependently. The guiding principle in this endeavor was a student centric approach to learning in order to provide the participants with an environment that would foster intrinsic motivation and in turn deep and high quality learning (Biggs, 2011). What makes this course particularly interesting is its inter-disciplinary nature touching upon topics in mathematics, physics and computer science. This inter-disciplinarity is in turn reflected in the diversity of the students as the course is equally offered to students from the three aforementioned disciplines. Indeed, in an initial constructive alignment analysis of the course these diverse backgrounds had been identified as a potential challenge for student's motivation, because they might already know part of the material or be overwhelmed by other parts. In order to account for this problem, the idea was to provide exercises that would cater to these different backgrounds and skill sets as well as to obtain frequent feedback from the participants about their experience with the lecture.

Special challenges: lockdown and online teaching

In addition to the anticipated diverse backgrounds of the students, unforeseen complications arose due to the worldwide epidemic in 2020. Since the course was taking place from April to May 2020, it fell completely into the lockdown period caused by the SARS-CoV-2 virus. Accordingly, the whole course had to be moved online, which necessitated additional adjustments to the lesson plan and naturally prevented certain planned activities such as small-group problem based blackboard sessions during the lecture. At the same time, being relegated exclusively to Zoom-meetings and online instructions the need for student activation and dialogue did present itself as even more urgent. Hence, in order to take this into account, I opted to adopt breakout-groups as a common theme during the lectures. This was done both in order to discuss self-prepared material in peer-groups before summing them up in the plenum as well as to work on assignments and problems that either exemplified concepts, just introduced in a lecture or to expose students to new aspects in a problem-based manner and prepare the scene for the next lecture/discussion. Furthermore, all lectures were recorded via Zoom and made available to the participants for later reference via Absalon.

Theoretical background

High quality learning that fosters a deep and long lasting understanding of the material is the gold standard for any successful teaching or learning activity. Traditional teaching approaches based on a teacher-based lecture style however do not promote student activity and engagement, which are the facilitators of these learning outcomes (Biggs, 2011). Instead, a student-centric perspective should be adopted at all stages of planning, executing and evaluating a teaching activity in order to facilitate high quality learning (Jørgensen, 2015). In such a learning context, students perceive the material as relevant and meaningful with respect to their individual situation and are given the opportunity to engage with the material in a self-led manner, increasing their intrinsic motivation. Indeed, learning contexts which encourage selfdetermined motivation have been shown to lead to higher quality learning (Bransford et al., 1999; Rigby et al., 1992). Within this study, we have implemented a number of techniques to encourage dialogue and student activation in particular taking into account the diverse backgrounds of the participants and which we will now describe in more detail.

Planned interventions

The planned interventions during the lectures consisted of the following techniques/topics.

Continuous course feedback after each lecture

In order to be aware and being able to react to problems and challenges for the students both with respect to the material but also due to the online format, feedback was requested from the students after each lecture. The feedback consisted of five open ended questions based on a pedagogical project form 2017 (Lutterodt, 2017). In addition, the idea was that this possibility to influence the lecture continuously would also increase student engagement and motivation.

IBM quantum experience as learning platform for quantum algorithms

Supplementing the theoretical and mathematical aspects and exercises of the course by implementing and running small algorithms and protocols in the IBM quantum programming environment Qiskit as well as executing them on an actual IBM quantum computer. The reason for including this module into the course was threefold. (1) To help to develop one of the ILOs namely the competency to analyze short quantum protocols (2) Since the introductory seminar about Qskit would be given by an external lecturer from IBM this part of the lecture would provide a connection beyond the specific topics of the course and demonstrate the relevance of the content of the lecture – at the same time it would give the course a small aspect of research led teaching as the students would use the same hardware as researchers in the field. (3) As an invitation to develop critical thinking, since the system is not error-free and hence all results have to be critically checked in order to ensure that the device functions in the expected manner. In addition, from the diversity perspective of the course this would give the computer science students an explicit exercise where they could make use of their prior knowledge and training to increase their engagement, whereas the mathematics and physics students would naturally have such an experience with regards to linear algebra or quantum theory, respectively.

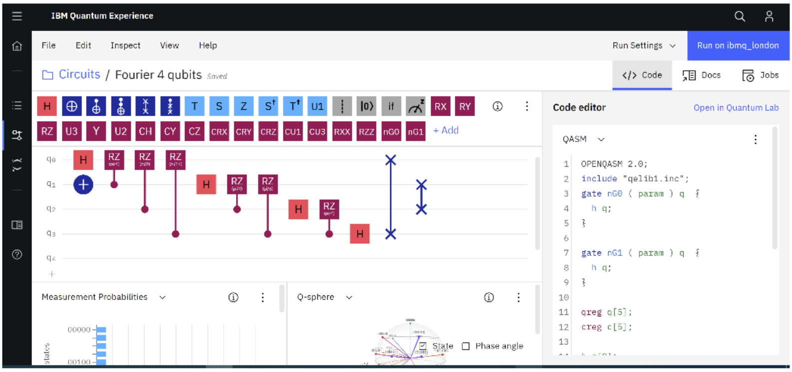

Fig. 19.1. Graphical Interface for IBM Qiskit.

In lecture assignments

Short assignments and group work during the lectures in breakout groups. The idea was to break up the lecture time into shorter periods to account for the reduced attention span during online lecture. In addition, to facilitate interactions between the students, which would also not have been possible otherwise via a common Zoomcall in particular for students with different backgrounds. These in-lecture exercises were accompanied by two exercise classes, the first one giving the students the opportunity to work self-dependently on the problems, but to be able to ask if they got stuck or had questions and the second in order to present and discuss their solutions of the exercises.

Evaluation

The overall impact of the described interventions where evaluated both with the standard course evaluation questionnaire supplemented by an additional survey implemented in Absalon, which more specifically asked about the experience of the students with the quantum programming exercises and Qskit. Furthermore, we obtained information via the continuous evaluation forms for each lecture. The complete questionnaire can be found in appendix C. An initially planned round of follow-up interviews with participating students was in the end not undertaken due to the corona restrictions and availability of possible interview partners.

Results and discussion

Before turning to the discussion of the three interventions, Let me briefly discuss the impact of the online regime for the course. Even though it was in general going rather well on a technical level, there were certainly challenges with concentration and active participation. Indeed, given the regular use of group work during the lectures as described in 3) in the planned intervention section, students found it very uncomfortable to present the results of their group discussions in the plenum via Zoom. As a way out of this dilemma, I then opted to use padlets where each group could briefly summarize their discussions, which I could then take as a starting point to sum up the major points by myself and ask further questions. However, this general shyness did reduce during the runtime of the course and should be attributed to the unfamiliar online teaching. In general, it was interesting to see how some adjustments of the lecture to accommodate for the online format would require surprisingly extensive discussions about the didactical contract of the lecture (Mørcke & Rump, 2015). Aside from the active oral participation in the plenum, the student's were also not comfortable with the idea of randomly assigned breakout groups. Here it took some discussion to explain to them that random groups and working with fellow students with divers educational backgrounds could actually be beneficial for solving the exercises. This was in fact also positively commented on, during the course evaluation, e.g. one student writes:

"We used Zoom's break-out-room function to put people in groups they weren't familiar with. This made people of different backgrounds work together and that worked really well (I think)."

However, other students' comments argue against the use of randomly assigned groups – at least if not everyone is interested in actively participating in:

"...the breakout rooms in zoom with just random people. They were useless for doing group work since mostly everyone was to shy to talk. Being able to pick who you are in a group with would solve this."

"...breakout rooms. 4 out of 5 times people do not use them, they are not talking. Make it so we can make our own groups."

Let me also mention that the anticipated diversity in the student's background could indeed be observed. In order to gauge the level of this diversity, I myself and my TA did initiate an introduction round via Absalon in which nearly half of the students participated in. The results of this discussion thread did reflect the different backgrounds present with larger than expected percentage of computer scientists present. In this context, the continuous and direct feedback after each lecture turned out to be a very helpful tool in order accommodate these individual differences. For example, it turned out after the second lecture, that the data scientist part of the students had not seen and worked with complex numbers before, which is however a central concept for quantum theory. Having been made aware of this problem then allowed me immediate to find a solution, i.e. by providing three short pre-recorded introductory videos about these topics.

Similarly, the input from these evaluations prompted me to rearrange the lecture schedule in dialogue with the students by moving one of the exercise classes in order to shorten the consecutive lecture time. The students did seem to appreciate this additional flexibility and their influence on the lecture, which is reflected in the following comment from the general course evaluation:

"They are flexible and willing to change everything if it gets a bigger learning outcome for us students. They had a evalutationion Absalon after each lecture (that people kind of forgot, sadly)."

However, as also this comment mentions at the end, unfortunately, the participation in the short evaluations dropped during the runtime of the course considerably from around 40the students to one or two participants. However, this problem might be overcome in an actual physical classroom-teaching situation.

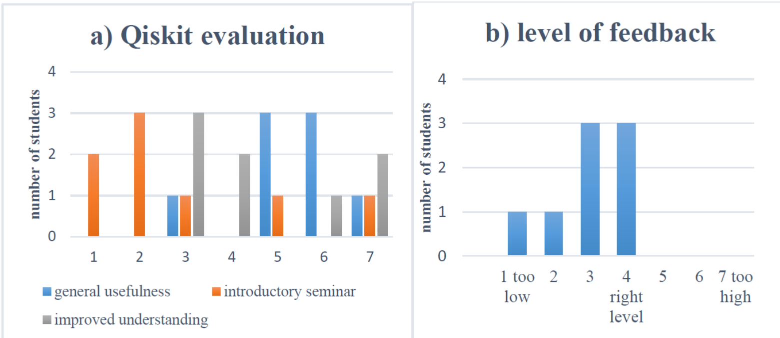

Fig. 19.2. Survey to IBM Qiskit. a) ratings of different satisfaction questions on the general usefulness, the improved understanding and the quality of the external seminar. b) Rating of the level of feedback provided to the students.

Finally, let us turn to the evaluation of IBM Qiskit as a tool for quantum computing exercises on which 9 out of 24 students participated. As can be seen in Fig. 19.2 a) the perception of the general usefulness of this tool is rather high among the participating students, followed closely by the ratings for the question whether it helps them to improve their understanding of quantum computing . However, the ratings for the quality of the introductory seminar turns out to be a bit lower. The level of feedback to the different Qiskit exercises on the other hand has been perceived as more or less adequate. These sentiments are also mirrored in the open comments, describing Qiskit as “usefull to acutall see the circuit in action and build it yourself to know exactly what each gate does” or “It made what we learn about seem more real”. Critical comments on the other hand are mostly concerned with making even more use of the Qiskit framework for the exercises, e.g. along the lines of “If the course should be more about the programming part of quantum computing, it would be nice to have more direct problems, especially problems where we have to figure out our own solutions” or “IT would be cool if you could make an exercise were you actually solve an unknown problem if there is someway to implement an oracle”.

In particular in light of these last comments, I could envision to integrate the Qiskit framework also within the classroom exercises where certain concepts could be introduced on the level of practical problems/algorithms as preparation for a devolutional final lecture. Going beyond this rather specific point with regards to quantum computing, I have the impression that the recurrent two minute course evaluations via open questions provided very useful and actionable information. This possibility of having an additional and well-rehearsed communication channel seems a very powerful tool for adapting the teaching to the actual needs and requirements of the participants in order to realize student-centered teaching.

References

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A Course description

NMAB19003U Introduction to Quantum Computing

Content
This course will provide an introduction to the field of quantum computing and information, covering a variety of topics ranging from computation and cryptography to foundations of quantum physics. Once familiar with the fundamentals, we will explore current research topics and discuss how quantum phenomena give rise to new algorithms for machine learning, quantum computational supremacy, cryptographic schemes with unprecedented security guarantees, and device-independent protocols.
As part of the exercises, you will run simple quantum programs on an actual, albeit noisy, quantum computer available through the cloud.

The specific topics covered include
- Fundamentals of quantum computing (quantum states, superposition, measurement, unitaries)
- The circuit model (qubits, unitary gates)
- Basic protocols (teleportation, super dense coding, state discrimination)
- Basic quantum algorithms (Deutch-Josza, Grover, HHL) and quantum computational supremacy
- Bell inequalities, non-local games, noncontextuality and device-independence
- Basic quantum key-distribution, bit commitment

Learning Outcome
Knowledge: the students will have an understanding of the basic principles of quantum information and computing, including knowledge of basic protocols, applications, and algorithms.
Skills: Carry-out computations corresponding to valid transformations of quantum states as a result of measurement or application of unitary gates.
Competencies: Ability to analyze simple quantum protocols and reason about basic information processing capabilities of quantum computers.

Recommended Academic Qualifications
1) Linear algebra: LinAlg or LinAlgDat course or equivalent
2) Basic probability: SS or DMA or StatFys course or equivalent

Teaching and learning methods
4 hours of lectures and 2 hours of exercise classes per week for 7 weeks.

Feedback form
Written
Oral
Individual
Collective
Students will receive written individual feedback on their assignement solutions. Collective oral feedback will be given during lectures and exercise classes regarding the problems/questions posed to the class.

Exam
Credit 7,5 ECTS

Type of assessment

Continuous assessment

Oral examination, 25 minutes

The students' performance will be evaluated via
- 3 individual, equally weighted assignments during the term
- Final oral exam (with preparation), where the student presents one randomly selected topic from a previously known list of topics

The assignments will account for 40% and the exam for 60% of the final grade.

Aid

Only certain aids allowed
All aids allowed for Assignments
Personally handwritten notes on paper allowed during the 25-minute preparation period before the examination.

Marking scale

7-point grading scale

B 2 minute evaluation

Question 1
What was the most important thing I learned in today's class?

Question 2
What from today's class remains unanswered or is still not clear?

Question 3
What would I like to improve?

Question 4
What am I going to use in the future from today's class?

Question 5
How did I feel about today's class?

C Qiskit questionaire

The four closed questions (1-4) had to be answered on a 7-point Likert-scale the remaining questions (5-7) were open comment questions.

Question 1
In general, I found that the use of the IBM Quantum experience was useful for the course Introduction to Quantum Computing (1: disagree, … , 7: agree)

Question 2
I found the external seminar on the IBM Quantum experience helpful as an introduction to the system. (1: disagree, … , 7: agree)

Question 3
Solving exercises in the IBM Quantum experience helped me to get a better understanding about the quantum algorithms discussed in the lecture. (1: disagree, … , 7: agree)

Question 4
The level of feedback on these practical exercises was
(1: too low, 4 right level, 7: too high)

Question 5
Describe some positive aspects of the practical exercises with the IBM Quantum experience for your learning

Question 6
What improvements would you propose to make the IBM Quantum experience more useful for your learning.

Question 7
Other comments and suggestions you would like to provide.