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Partial re-designing of the quantum information course: Adapting to advances in the field

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Problem description

The *Quantum Information* course offered to the masters and PhD students at the Niels Bohr institute until 2016, was designed approximately ten years back. It was created to educate students in the basics of quantum information sciences. The course covers a wide variety of topics with a good balance between theoretical concepts and applications. However, over the past decade the field of quantum information have advanced substantially, and has become quite interdisciplinary. Furthermore, newer physical systems and technology has been developed to implement information processing at atomic levels. As such updating the course with some of the latest material and concepts is warranted. It is also necessary, to maintain the quality of the course at a standard, comparable to that offered in other top universities in Europe and North America. As such, in addition to including new material one needs to also re-define the intended learning outcomes (ILOs) of the course, which are even, not well aligned to the present version of the course .

Course structure

The course *NFYK13005U Quantum Information* is an elective course of 7.5 ECTS points offered to masters students and beginning PhDs. The course aims at teaching students how to implement information processing (communication, computation, measurements, etc.) more efficiently by exploiting the principals of quantum mechanics. Generally, there are 20-25 students in the course among which about a fourth, are pursuing PhDs in topics related to quantum information science. Quantum mechanics and advanced quantum mechanics is a pre-requisite to this course. It is quite helpful to have some exposure to laser physics and/or quantum optics though not necessary.

Intended learning outcomes (ILOs)

The course description (kurser.ku.dk) breaks the ILOs of the course into three broad areas, skills, knowledge, and competences (see Appendix A). In general the ILOs are well laid but not necessarily aligned to the course. For example, according to the skill sets, the students are supposed to be able to discuss how decoherence and imperfection appears. In practise though the course lacks substantially in this parts of the skill set. Furthermore, when we introduce new systems and technological aspects of the field, the ILO will become even less aligned. The competence aspect of the course to some extent is sound. Finally, as for knowledge, the course lacks in providing the students with it in several areas. I will discuss this in detail later in section 3. A substantial part of this misalignment comes from the fact that the course has not been updated to reflect the later developments in the subject.

Learning activities and instructor's responsibility

The course has two instructors, with me being one of them. The workload is equally divided among the course instructors. A typical week involves 3 (4 x 0.75) Hrs of lectures, 3 (4 x 0.75) Hrs of exercise solving sessions (given about a week in advanced to the students who are supposed to have tried to solve it already) guided by the instructors, and 1.5 (2 x 0.75) Hrs of journal paper discussion (papers are also given to students one week in advance). The exercises are typically made at a level 1 of pedagogical teaching (Herron, 1971; Tamir, 1989). The weekly bulletin in course homepage gives brief summary of the different teaching learning activities that will be undertaken in that week, and contains links to course material, exercises and journal articles. This is typically uploaded one week in advance.

Assessment

Assessment for the course is done by an oral exam of 0.5 Hr by instructor and one censor (internal). There is no feedback on exercises (except during the solving sessions) and nothing from the exercises or article reading and discussion directly contribute towards the evaluation of the final grade for the course.

Constructive alignment

I will discuss the issues with the course in terms of the constructive alignment model put forward by Bigg's (Rienecker, Jørgensen, Dolin, & Ingerslev, 2015). This model suggest that for optimal student learning the ILOs, should be aligned with the learning activities, and the assessment. As pointed our before, there are issues with the ILO's. To discuss this issues I will also follow two perspectives, namely the students perspective and the colleague perspective. Before going into further discussions, I should mention that the ILOs were written before I had any pedagogical training and any knowledge of its importance. The course ILOs were just a follow up from an old version, that my senior colleague who used to teach this course alone had.

Students perspective: The ILOs for the course is not optimal. Let me now discuss the primary reasons behind this judgement. I believe we have way too much information in the ILOs which to certain extent is a bit vague also. For example, we write, "discuss how decoherence and imperfections appear and influence experiments and know how to describe it in terms of the density matrix". In reality we actually only partially follow this in class. It is actually quite hard to discuss this topic without going into details. Thus, certain part of it also becomes vague. I have observed while teaching how much students struggle to grasp this concept.

The ILOs to certain extent speak about student building some understanding about experimental implementation. It is impossible to achieve this as both of us (the instructors of this course) are theoretician. Even though we discuss some experimental papers as a part of the course the student not necessarily build up the required expertise from this. The course is heavily biased, as far as choice of physical systems for implementation of quantum information protocols are concerned. We have completely ignored the solid state quantum computing and information stuff. This currently account for almost 40% of the field. The ILOs do not acknowledge this fact. It also unnecessarily favours students with quantum optics background, when it is not a requirement for the course.

Finally, we talk about students learning quantum cryptography and error corrections, when in practise we can hardly accommodate these topics due to time constraints. We end up giving students some flavour of these topics which by no mean can help them gain expertise. I will however say that the learning activities that we employ for this course in the form of lectures, exercises and journal article discussion sessions are to some extent adequate and well linked to each other. They are done in a way so that the concept introduced in the class becomes clearer while doing the exercise. Furthermore, the students get the feel of the state of art in the field by reading some latest journal article.

As for assessment, we have an oral exam for about 30 mins for each student where we check for whether they acquired the expected skills or not. My observation is that, this assessment scheme is suitable to the students who have previous exposure to this kind of a examination scheme. In general it proves to be very challenging to students (typically internationals) who have never before participated in a similar exam. Hence in its current form the assessment is biased towards certain groups of students.

Colleague perspective: There are two instructors for the quantum information course, I am accompanied by another senior colleague. He was the one who was teaching this course all by himself before and had created the ILOs for the course. Currently we share jointly the responsibility of the course with the total workload equally shared. However, for the material of the course like lectures and exercises we use a lot of the stuff that he had created earlier. During the course, we have some meetings with an objective to build coherence in the course. However, there are certain key issues regarding this that I will discuss next.

My colleague is a bit conservative regarding making any drastic change to the course. From several years of teaching experience, he judges the course to be well tuned. Even though he acknowledges the problems with ILOs but seems to prefer little change at a time. Having much less teaching experience, I am also not fully confident in its outcome and hence also find it is difficult to convince him in these regards.

The course material and the exercises are tuned to his way of teaching which is not necessarily same as mine. This create some issues for me when I am trying to validate certain task. For example, I become unsure of the boundaries to which we go, while discussing a question. Finally, my colleague is an awesome teacher and have vast (more than 10 years) pedagogical experience, as such I find it difficult to match his insight on student learning experience. This then concerns me, as to whether students are getting the required and relevant understanding on the topics I am teaching.

Proposed solutions

It is evident from the above analysis that there are several areas of improvement to create better constructive alignment for the course. To start with, one needs to address the issues in the ILOs. In brief we itemize the issues with the course and their possible solutions below.

1. Need to write a new ILO which should be more concise and a truthful reflection of what students should expect to achieve from the course.
2. Introduce new course material for solid state quantum computing and decoherence. This topics are crucial for implementation of quantum information protocols and hence needs more weightage than currently given.
3. Modify assessment method to better judge the skill acquired by student in the course. Since the course does not have huge enrolment, a possible solution can be to introduce a writing assignment like a short report on topics covered in the course in addition to exam and put 25-30% weightage of the final grade on this.
4. Build better synergy between the instructors by having in-depth discussion about what will be covered and how will it be done.
5. The ownership of course material and assignments should be equally shared between the instructors.

Re-designing the course: Implementation

Phase -1: Discussion with senior colleague and restructuring the project.

Before the beginning of the course in block 4 of 2017, I had a detail discussion about the above listed issues and the possible solutions, with my senior colleague. He was quite supportive of my proposals. However, due to university policy on timeline (about two year in advance) of updating ILOs we decided to keep the same ILOs as 2016 while including additional information on the course home page for the students. We agreed on designing new ILOs for future. He also agreed upon including new material, but in a gradual form. We decided to include course material on solid state quantum information and computation for 2017 and kept for 2018, the required changes on the topics of decoherence.

He realized the importance of co-ownership in course material and assignments. But suggested that we should consider a gradual process in this regards. My understanding is that from his years of experience in teaching, he fears a complete derailment of the course, if this process is implemented suddenly. I appreciate his input in this regards and have started to gradually build my own material and exercises. One thing that we both found necessary was bring some new challenges nin the learning process for the students. For this we plan for example to introduce some open end problem sets for the course to be given in 2018. We also agreed on building a better synergy between us by having detail meetings for preparation of lectures and assignments. Since he knew that I am undertaking the KNUD course, we agreed that in a few of the lectures and assignment sessions I will test some of the pedagogical methods.

Unfortunately, we struck an impasse on the issue of assessment. My colleague even though understood my concern, however he is also of the feeling that oral exam is the optimal method of a assessment given the number of students and the time frame for exam. However, he did agree to create a standard questionnaire for the final exam that may be followed by us in the oral exam to judge the skill of students starting 2018. I am not fully satisfied with this solution and is still looking for a better method of assessment for this course.

Phase-2: Discussion with Pedagogical supervisors.

I discussed with the pedagogical supervisors about the changes that will be implemented in the course and the methods of teaching that will be used. I gave them the new course materials in terms of lecture notes, assignments and some articles that will be introduced in the course of 2017 for discussion. I also told them that I planned to use different pedagogical methods in adherence to the theory of didactical situation. In particular I considered standard lecture, peer review with group work and inductive teaching and learning. The supervisors showed lots of encouragement and gave vital inputs in pre-supervision meetings like, whether the newly introduced material are readable or not, how to make standard lectures more interactive, how much material should one consider in sense of time for inductive teaching and so.

Phase-3: Execution

As part of course re-designing, I implemented the following in the *NFYK13005U Quantum Information* course that I taught in *block 4 of the academic year 2016/2017*,

1. Prepared weekly summaries of what will be covered in the following week and published it in the course webpage along with reading material and exercises for students. In this way, we were able to better align the ILOs with the teaching activities (see Appendix B).
2. Included new reading material on solid state qubits for students to learn how these qubits are engineered and what can be done in quantum information.
3. Included new reading materials on how to make solid state quantum logic gates.
4. Included new reading materials on quantum algorithms.
5. Included two new lectures on solid state quantum information processing (see Appendix C).
6. Included new exercises on the physics of solid state qubits and on solid state quantum gates (see Appendix D).
7. Included two new research articles for discussion. The objective here was to make students understand the practical implementation of concepts of quantum information like creation of entanglement and making quantum logic gates using solid state qubits (see Appendix E).
8. Gave comments on several other exercises to co-instructor and helped him in improving their structure and explanation.
9. Implemented new methodologies for teaching like formative feedback, peer reviewing and inductive teaching (Black, Harrison, & Lee, 2003; Boud & Falchikov, 2006; Liu & Carless, 2006; Hounsell, 2008; Prince & Felder, 2006; McDermott, n.d.).
10. Created and used a questionnaire with some particular set of important questions for the final oral exam to help judge the skills of students.

Re-designing the course: Outcome

Aligning the ILOs with advanced summary of the coming week

The students appreciated this and felt that it helped them to prepare themselves for the material to be presented in the week. Also it gave them a clearer idea about what to expect from the course.

New course material and lectures

Students very much appreciated introduction of the new topic on solid state quantum information and computation. They however gave some crucial feedback that will help us to improve the course. For example they felt that the study material is too condensed and it is difficult for them to decipher it completely. I also realized it while teaching and could see a clear lack in preparation on their part. Some of them also find it difficult to connect the different inherent concepts on this topics due to lack of a more general introduction (see Appendix F).

As for the new material on quantum algorithms they were quite satisfied and enjoyed it. However, they did not like my inductive teaching and learning method for this topic. According to pedagogical supervisors, who were present in the session, the topic turned out to be too abstract to do in the inductive manner. They further said that, such topics need lot of experience of teaching to implement in the inductive method.

New exercises and execution

In general the students were satisfied with the problem set for the exercises, the corresponding discussions on it and also on the overall execution of it. However, they did said that the exercises where a bit hard, and also that they expect to see a more descriptive questionnaire for such exercises. They were critical about my approach to the discussions. Students felt that with the goal of making the session very interactive, I was actually pushing them to get involved in the discussions which was stressful to some (see Appendix F).

Research article discussion

Students liked this part of the course most. They were very satisfied even though they not necessarily understood all of the scientific article. In their feedback they mentioned that getting exposed to something like this was itself a fantastic learning experience. They also appreciated very much that very recent and relevant scientific articles were discussed. They also appreciated the guidelines, that we have prepared and given them with the articles, to help them understand them better (see Appendix F).

Assessment

The students were assessed and graded, on the skills they have built from the course, via a final oral exam of about 30 mins per student. Of the 30 mins the students gets 2 mins for preparation on the topic they will be examed. They have 15 mins of presentation and 10 mins on general question answers. For this exam I created a standard questionnaire to judge the potential and level of expertise of the students. The oral exam was taken over a period of two days to complete assessment of all students. During the first day of exam, observing the effectiveness of the standard questionnaire for student assessment, both my colleague and the sensor started using it to judge the skill of a student. I believe in this way we were able to create an unbiased assessment of all students. I believe as a result of this a high percent of students (bout 68%) of the 25 students who took the final exam got grades 7 and higher. We did agree after the exam, to further refine the questionnaire by discussing between us before next course year.

Conclusions

In general the project on partial re-designing of the course was successful. All the feedback and constructive criticism (see Appendix F) that we received from the students will be very helpful for further improvement of the course. As has been discussed above, there are still some issues and loopholes in the course that we need to address. Also, following student feedback I am in the process of writing some of the course material by myself as the existing ones in the literature are indeed quite condensed. Furthermore, there will be some restructuring of the exercises, lectures and my teaching styles following students feedback. Finally, there is still the question of finding a newer and better method of assessment. **The course was rated A by the Undervisningsudvalget (teaching committee) of Niels Bohr Institute, an improvement over the last rating of B that it got in 2016.**

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A Present ILOs continuing since 2016

NFYK13005U Quantum Information

Volume 2017/2018

Expand all

Education

Content

Learning Outcome

Skills

After the course the students should be able to explain how the various quantum information protocols work and why they are better than any classical protocol. Furthermore the students should be able to describe how to implement quantum information protocols in practice and discuss some of the problems, which arise when one tries to do so.

More specifically the students should be able to:

- describe how the BB84 quantum cryptography protocol works and how it is implemented in practice.
- define entanglement for pure states, and describe how to use it for super dense coding, cryptography, and teleportation.
- explain how entanglement may be generated experimentally for photons, ions and atoms.
- explain what a quantum computer is and describe how the Deutsch and Grover algorithms and quantum simulation work on a quantum computer.
- discuss general requirements for practical implementation of quantum computation and describe how these requirements are fulfilled for an ion trap.
- explain the teleportation protocol and how it may be implemented experimentally.
- explain Bell's inequalities and their violation in quantum mechanics
- discuss how decoherence and imperfections appear and influence experiments and know how to describe it in terms of the density matrix.
- relate the various parts of the course together and apply the knowledge gained in the course in new situations.

Knowledge

After the course students should know the elementary concept from quantum information theory including qubits, pure and mixed states, Bloch sphere, entanglement, super dense coding, teleportation, quantum repeaters, Bell's inequalities, entanglement purification, quantum error correction, and quantum computation algorithms (Deutsch, Grover, and quantum simulation). Furthermore they should know how one can implement quantum information processing in simple experimental systems such as photons and trapped ions.

Competences

The student will learn how the different logical structure of quantum mechanics, compared to classical mechanics, enables new possibilities for e.g. computation, measurements, and communication. Thereby the course will provide a deeper understanding of the quantum mechanics learned in previous courses. It will also provide the students with a background for further studies within quantum optics or quantum information, e.g. in a M.Sc. project

B Weekly bullentin to fix the ILOs on an ad hoc basis

03/01/2018 Week 6: 5030-B4-4F17;Quantum Information

Introduction to ion traps (https://absalon.instructure.com/courses/17101/files/934012/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/934012/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/934012/download?wrap=1)

"Quantum optical implementation of quantum information processing" by J.I. Cirac, L. Duan, and P. Zoller (http://arxiv.org/abs/quant-ph/0405030) p 6-8 and 12-17.

Movies illustrating the collective motion of ions can be found here (https://www.osapublishing.org/oe/fulltext.cfm?uri=oe-3-2-89&id=63302#articleSupplMat).

Tuesday

Lecture:

In a previous lecture on solid state qubits we learned about superconducting qubits and how to implement single qubit rotations. In this lecture we will advance further and learn how to use superconducting qubits to make two qubit quantum logic operations. This is of great importance from quantum computation perspective as eventually a quantum computer build with such qubits will perform thousands of such logic operations. We will first learn how to couple two superconducting qubits. Then we will learn how such coupled qubits can be harnessed to build a CNOT gate.

This is currently a hot topic in research and as such it is hard to find some pedagogical material for reading. However we will soon upload some notes on how to couple two superconducting qubits which you may find useful to read. We will also after class upload the lecture notes. In the meanwhile you may want to look at this short article (http://web.physics.ucsb.edu/~martinisgroup/papers/Martinis2012.pdf) by John Martinis, one of the pioneers in this field.

Literature: Coupling superconducting qubits (https://absalon.instructure.com/courses/17101/files/1326315/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/1326315/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/1326315/download?wrap=1)

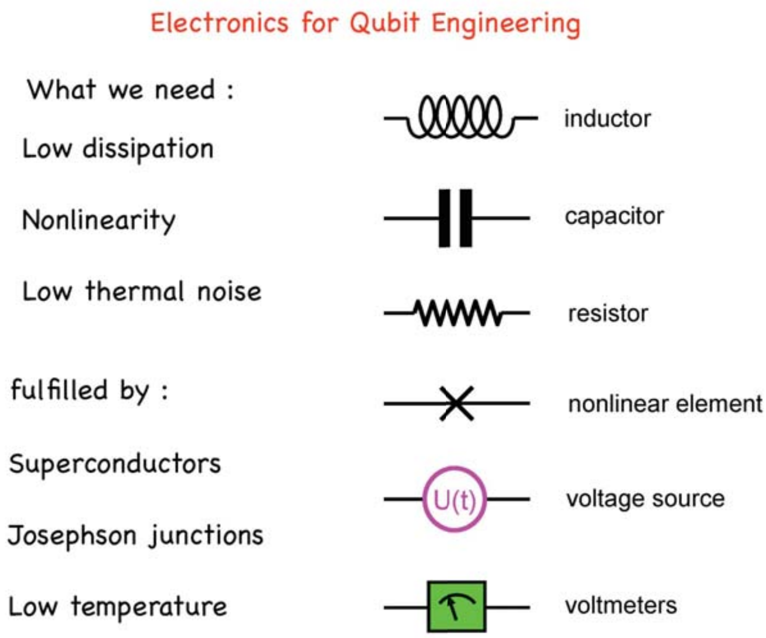
Exercises

In the second half of the class we will solve two exercises. The first is on how to create entanglement in an ion trap (https://absalon.instructure.com/courses/17101/files/934041/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/934041/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/934041/download?wrap=1). The second is on adiabatic elimination (https://absalon.instructure.com/courses/17101/files/934022/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/934022/download?wrap=1) (https://absalon.instructure.com/courses/17101/files/934022/download?wrap=1). The last one is less important than the first and we may not have much time to discuss it. If we don't it is not a major problem.

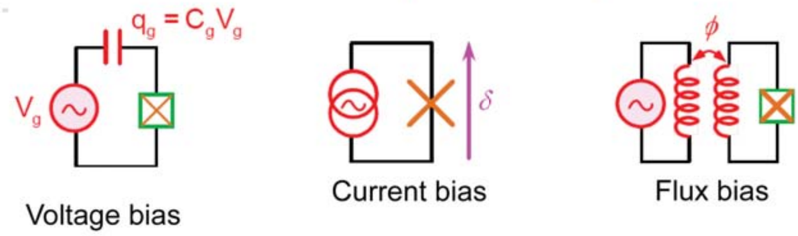
Friday

https://absalon.instructure.com/courses/17101/pages/week-6?module_item_id=307918 2/3

C Sample of lecture notes on newly introduced course material



Hamiltonian of Superconducting circuits



Hamiltonian:

$$\mathcal{H} = \frac{(q-q_g)^2}{2C_{\sum}} - E_J \cos\theta \quad \text{Voltage bias}$$

$$\mathcal{H} - \frac{\phi\phi_0}{2\pi L}\theta \quad \text{Current bias}$$

$$\mathcal{H} + \frac{1}{2L}\left(\phi - \frac{\phi_0}{2\pi}\theta\right) \quad \text{Flux bias}$$

D Sample exercise

Solid State Qubits

Sumanta Das

(Dated: April 27, 2017)

Problem (2) in this exercise is actually a prelude to problem (1). However given that the course is on quantum information we put more stress on concepts/ideas or problems linked to it. Hence we decided to give problem (1) priority over problem (2). We though encourage you to try out problem (2) as it is quite interesting and cool from a fundamental point of view and by doing it you will learn a lot.

Problem 1: Hamiltonian of a superconducting charge qubit

(a) Starting from the Hamiltonian in the cooper pair number basis introduced in the class $\mathcal{H} = \sum_N 4E_c(N - N_g)^2|N\rangle\langle N| - \sum_N \frac{E_J}{2}(|N\rangle\langle N+1| + |N+1\rangle\langle N|)$, and using the discussion provided in the attached material (see last page) show that near the degeneracy point $(N_g \simeq 1/2)$ one gets the cooper pair box qubit Hamiltonian in the form

$$\mathcal{H} = E_z\left(X_{control}\sigma_z + \sigma_x\right) + \text{unimportant constants.} \quad (1)$$

Note that we have a factor of 4 in front of the charging energy E_c which is absent in the reading material. This factor arises from whether one considers the charging energy of a single electron or a cooper pair. You should not be worried about this and the physics of the problem does not change.

(b) What are the terms E_z and $X_{control}$? Express $X_{control}$ in terms of gate voltage V_g using $N_g = C_gV_g/2e$, where C_g is gate capacitance.

(c) What is the Hamiltonian in Eq. (1) at the degeneracy point $(N_g = 1/2)$?

(d) What are the eigenstates and eigen-energies of the Hamiltonian in (1) at the degeneracy point $(N_g = 1/2)$?

(e) Diagonalization of the Hamiltonian in Eq. (1) gives the energy level diagram shown in figure 1(a). Find the eigen-energies of the Hamiltonian (1) ? Can you see the nature of the energy levels from the eigen-energies you have calculated

E Sample questionnaire to discuss journal article

Manipulating the quantum state of a charge qubit

Sumanta Das

(Dated: May 1, 2017)

This exercise is not the usual type where we solve and discuss a set of problems related to concepts introduced in the lectures. Instead we want you to a read an experimental article where a solid state qubit, specifically a superconducting charge qubit was engineered and controlled manipulation of its state was achieved for the first time. The article we are going to study is: D. Vion, A. Aassime, A. Cottet, P. Joyez, H. Pothier, C. Urbina, D. Esteve and M. H. Devoret, Science **296** 886 (2002). We will discuss what goes on in the experiment and how they achieve control over the dynamics of the qubit state. Below we list a few questions, which can form the basis for discussion of the article. However this is not an exhaustive list and you are encouraged to also include some of your own thoughts during the discussion. To have a fruitful discussion on the article it is **essential that everybody at least read the article before the class** and preferentially also thinks about the list of questions provided below.

Note that while reading the article you will come across a discussion of the readout of the qubit. It is kind of difficult to understand and is not essential for understanding other cool things in the article. Hence you may skip over that part and need not be worried if you do not understand it.

(a). In the article it is said that for the Cooper pair box to be represented by the Hamiltonian $\hat{H} = E_{CP}(\hat{N} - \hat{N}_g)^2 - E_J \cos\hat{\theta}$ one needs the Coulomb energy E_{CP} and the temperature T to be smaller than the superconducting gap Δ. Do you understand why one needs to satisfy these conditions ?

(b). Can you detect the elements of the quantronium circuit in the scanning electron micrograph of Fig. 1(B). Note that, finding resemblance between the schematic circuit diagram in Fig. 1(A) and the scanning electron micrograph of Fig. 1(B) is not simple. Try to detect the Cooper pair box, the Josephson junctions, and the leads for external voltage control of the system.

F Student evaluation

What was good about the course? Why?

Very interesting subject overall.

Very interesting topic! Interplay between abstract theory and (even though typically rather involved...) current research papers was very rewarding - its nice to see people outside the course cares about the things discussed.

Exercises were difficult, but help from Sumanta and Anders helped a lot. Office hours is an amazing offer, even though I only used it sparingly, I benefited a lot from them.

The application of quantum mechanics really is a good practice for all physicists to strengthen their understanding. So this course really took me off guard, since it was a bit more theoretical than assumed, but it was a nice surprise!

I think that working with relevant scientific papers has been interesting and I have gained much knowledge from the discussion segments. I thought the articles were accessible and a good level of difficulty with our background knowledge from the course.

I generally think the reading material was well chosen and helpful.

The exercises were great! They were fun to do, felt very relevant and almost every exercise had some surprising result.

Very good lecturers and interesting topics.

The Qdev article was too technical to read (I almost died of boredom) but the following discussion was very useful and it was cool that Casparis was brought in.

I thought the Superconducting Qubit review was horrific to read - a big mess - and I had to spend a lot of time on my own and in discussions with friends to figure out what was going on in this topic.

In a few of the exercises, it was difficult to understand what exactly one was supposed to do.

Generally there was never enough time to complete the exercises in class. If this is on purpose, it would be good to let the students know that they are supposed to start work on the exercises before class.

Sometimes the use of certain didactic tools seemed a bit forced (like the "discuss with your neighbours" things), but I guess that is the sort of stuff that comes with experience as a lecturer.