Project work.

A project is (normally) carried out by two students working together. The different suggested subjects are briefly presented below and the respective supervisor is given. A more detailed description of each project is provided in discussions with the supervisor. Students should not hesitate to have regular contact with their respective supervisor during the project work in order to get continuous feedback.

The project should be presented in a written report of approximately 15 to 20 pages. The written report should be handed in to the supervisor at the latest Thursday May 23rd. The dates for the oral project are Wednesday May 29th and Monday June 3rd. The exact times will be for the oral presentations will be given at the latest Thursday April 24th. Until then please keep at least one of days free (8-17). For the oral presentation, the main results of the project should be presented by means of powerpoint/pdf or equivalent software in front of the other students of the course. The project is intended to take 70 working hours per student, including report writing and oral presentation. Some advice and instructions regarding the oral presentation is provided at the end of this document.

Subjects.

1) Quantum simulators (A. W.)
In the eighties, Feynman gave the first hint that one would need the power of the quantum world to efficiently calculate systems containing quantum information. The first idea did not involve general quantum computers however, but rather quantum simulators. In this task, describe what a quantum simulator is, how it is different from a quantum computer and how it fits in to the general development of quantum information technology. What is the difference between an analogue and a digital quantum simulator? What experimental efforts have been made so far and what is feasible in the future?

2) Free space quantum communication (A. W.)
One way to realize long distance communication without fibres and quantum repeaters, is to entangle photons from distant parties using orbital satellites as middle stations. This would require the ability to send single photons in free space (through air and other background gases) a distance from the earth surface up to the satellites. Describe the ideas behind this communication protocol, how does this create a quantum link between the two parties? How much of this that has been experimentally tested and what remains? What are the major difficulties in realizing such a scheme? (Also, if anyone is doing the Quantum repeater project, potentially discuss with them about pros and cons of each scheme in terms of a future global quantum communication network.)

3) Quantum computation with spins in quantum dots (P. S.)
A decade ago Daniel Loss and David diVincenzo proposed a scheme for quantum computation based on single electron spins in semiconductor quantum dots. This proposal has generated large theoretical and experimental interest and is now considered to be one of the most promising candidates for quantum computation in the solid state. In the project you are going to investigate the original proposal and describe the schemes by which universal quantum computation is made possible. You should further perform an analysis of the theoretical and experimental development during the last decade and discuss the progress in relation to the diVincenzo criteria for a successful hardware implementation of a quantum computer. Given the present status of spin-based quantum computation with electrons in

quantum dots, discuss and assess the main qualitative and quantitative obstacles for an ultimate realization of the proposal. What are in your opinion the best remedies for the identified problems? Based on the acquired knowledge, speculate about the long term possibilities for the spin-based quantum computer. Will a working quantum computer based on the Loss-diVincenzo proposal ever be constructed?

4) Bell inequality: quantum non-locality vs. local realism. (P. S.)
Starting with the debate in the mid 1930's between Einstein, Podolsky and Rosen on one side and Bohr on the other, the subject of interpretation and philosophical implications of quantum mechanics has continued to fascinate physicists as well as laymen during almost a century. While Einstein found the philosophical implications of quantum non-locality unacceptable in that they violated either locality or realism (or both), Bohr argued that they were simply a natural consequence of the basic principles of quantum mechanics. With the inequality of John Bell it became possible to start to compare quantum non-locality with local realism via experiment. So far all experiments have pointed in favour of quantum mechanics, however the interpretation of the experiments have been intensively discussed. In the project you should present a historical account of the theoretical discussion including the Einstein-Bohr controversy, von Neumann's "impossibility proof", Bohm's two-spin model and Bells inequality in its most important forms. In addition key experiments attempting to violate the Bell inequality should be discussed. The meaning of loopholes, mainly the locality and the detection loopholes should be explained. Based on the obtained knowledge, give your opinion about the present status of the question about quantum nonlocality vs local realism. In your opinion, given that the question could be unambiguously settled, what would be the main philosophical implications of a quantum non-local and local realistic description of the world respectively? What differs between the situations where either locality or realism has to be thrown overboard.

5) Entanglement: concept, measures and open problems. (P. S.)
Introduced as concept by Schrödinger, entanglement initially was at the heart of the discussions about the philosophical implications of quantum mechanics. In recent decades, it has become increasingly clear that entanglement, or quantum mechanical correlation between different parts of a system, constitute a resource for various quantum information and quantum computation tasks in the same way as energy for a mechanical process. This notion has naturally led to an interest in quantification of entanglement. However, the research has in recent years demonstrated that such quantifications are far from trivial. In the project you should present an overview of the present status of entanglement research. In particular you should discuss the measures for entanglement of a single system (a qubit in the simplest case) with respect to an environment as well as the entanglement between two or more subsystems. Examples of important concepts and measures are e.g. von Neumann entropy, negativity, entanglement of formation and distillation and concurrence. Here both pure and mixed states are of importance. Based on the different measures discuss the entanglement of central two- and many-qubit states as e.g. Bell states, GW-states and Z-states. Based on your acquired knowledge, discuss what you think is the most central property for an entanglement measure. In your opinion, will there ever be a final theory for entanglement?

6) Quantum computing in rare earth ion doped crystals (S. *K.*)
The diVincenzo criteria *Fortschritte der Physik*, 48, 2000, 9-11, 771-783. (http://onlinelibrary.wiley.com/doi/10.1002/1521-3978(200009)48:9/11%3C771::AID-PROP771%3E3.0.CO;2-E/epdf) outlines what is needed to construct a working quantum computer. A quantum computing scheme based on ions doped into inorganic crystals is

experimentally pursued in Lund. Explain the scheme and analyse it in terms of the diVincenzo criteria. What are the strong and weak points and the experimental status of the scheme? (Also, if anyone is doing project 3, *Quantum computation with spins in quantum dots,* discuss with them about pros and cons of the two schemes.)

7) Quantum repeaters (*S. K.*)
Today the market offers commercial quantum cryptography equipment that can be directly interfaced to the standard telecommunication net. However, the maximum distance for quantum cryptography (quantum key distribution) along the optical fibre net is essentially limited to distances less than 100 km due to attenuation in the fibres. As for classical long distance optical communication, long distance quantum communications requires repeaters and more specifically, quantum repeaters. A quantum repeater is a quite sophisticated device requiring quantum memories, quantum teleportation, entanglement swapping and entanglement purification. Describe how a quantum repeater works by describing the quantum teleportation, entanglement swapping and entanglement purification processes. Briefly relate to the present status of the experimental work on quantum teleportation, entanglement swapping and entanglement purification (If anyone is doing the “Quantum memories” you might discuss with them on the experimental status on quantum memories.

8) Quantum memories (S. K.)
Analogous to classical computing and processing, quantum information operations require the ability to store quantum data, i.e. superposition states and entangled states. One of the more successful schemes is based on storing quantum states in ensembles of ions in rare earth crystals, a scheme which also is pursued in Lund. Here a single photon can be stored in a collective excitation of billions of extremely weakly excited ions. Describe how quantum memories based on rare earth crystals work and explain and give examples of experiments from the literature where entangled photon pairs where single photons have been stored and recalled.

9) Quantum computation with superconducting qubits. (*Ville Maisi*)
One and a half decade ago it was demonstrated that superconducting circuits could be used as quantum bits. This lead to an outburst of research both theory and experiment, on the properties of a potential superconducting quantum computer. Half a decade ago another important step was taken when it was demonstrated that the controllability and decoherence properties of superconducting quantum bits were strongly improved by putting the qubits into microwave cavities. Today it is possible to carry out simple calculations on rudimentary superconducting qubit quantum computer through the cloud https://www.research.ibm.com/ibm-q/qx/. Describe the experimental and theoretical development of the superconducting quantum computer.

10) Majorana qubits & topological quantum computation (Martin Leijnse)
So-called topological states offer the possibility to encode quantum information in a way which is, in principle, immune to decoherence. It is also possible to manipulate such topological qubits in a robust way, using protocols where the outcome is always exactly the same and independent of experimental errors in the implementation of the protocol. Topological quantum computation was long considered little more than a theoretical physicists dream, but recent experimental progress in realizing topological Majorana bound states in nanowires coupled to superconductors has motivated an explosion of experimental activities in this field. Describe why a topological qubit has, in principle, the potential to

outperform any other qubit, how it can be implemented in a nanowire device, and what experimental problems are faced and make even such a qubit imperfect in reality.

11) Beam up my quantum state, Scotty! (P. S.)
In the science fiction movie Star trek Captain Kirk and his crew can be teleported through space. While it, according to the laws of physics, is impossible to teleport matter itself, quantum physics opens up for the possibility of teleporting the quantum states of matter. This idea was proposed theoretically in 1993 and demonstrated experimentally four years later. To date the world record is teleportation over 16 km, discuss and describe the theoretical and experimental development of quantum teleportation and how it can be used in various quantum information and computation tasks. Explain the role of quantum entanglement in teleportation and how it is compatible with the no-cloning theorem for quantum states. Also explain why it does not allow information transfer faster than the speed of light.

Instructions for the oral project presentation

The course grade is based on your oral and written presentations. Below some points which should be useful for you to consider when preparing your presentations have been listed.

1. What are your main results/conclusions and what is the main message that you would like to communicate? Suppose that you had not done this project and someone else would have presented the project for you. Think about what would have been the most useful/important/interesting for you to know about the project in that case. This is then probably also what you want to tell the others about.

2. Be very clear on what the project is about. Be careful to give a proper background. Make sure that the audience understands the overall perspective.

3. Based on how much time point 2 above will consume of your 20 minutes, select what you deem most important to explain further in order to make the audience better understand your full work.

4. It may be good to keep in mind that calculations are in general appropriate and often necessary for your written report and the audience will always be able to read your report and get all these details. In your oral presentation, however, you would typically very restrictive when it comes to any detailed calculations, while it of course could be useful and maybe even necessary to write defining equations and explain these. When it comes to numbers, order of magnitude of calculation results can be interesting, but normally mentioning more than one (or possibly two) significant digits probably just takes focus away from more important things that you wish to say.

5. Have **at least** one complete rehearsal of your presentation. Decide what you will write on the board and who will write it (when you are two persons it can be efficient if one person writes/draws while the other one talks and vice versa). It is often also good to think about where on the board things should be written. Also remember that “one figure can say more than a thousand words” and you do wish to use your presentation time efficiently in order to communicate your message as well as possible.