# Quantum computing proseminar SS2022:
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| Quantum code cracking | (Posske) |
| Topological quantum comp. and its simulation: Fibonacci anyon fusion and braiding | (Ioannidis) |
| Quantum annealing and machine learning | (Posske) |

*particularly suitable group projects

# Quantum computing proseminar SS2022:
# List of topics - Extended

## Scientific applications and algorithms

***Shor's algorithm (Quantum Fourier transform and discrete logarithm)**
*Background*: Shor's algorithm factors integers qualitatively faster than classical algorithms. The algorithm is involved and consists of subparts, e.g., the quantum Fourier transform and the discrete logarithm. This project is a suitable group project.
*Areas*: Mathematics, algorithms
*Task*: You learn about Shor's algorithm, the underlying mathematics, and understand Shor's algorithm and its parts.
'hands-on' task: You implement your own version of Shor's algorithm and let it factor small primes.
*Sources*:
-Shor, P. W. (1997). Polynomial-time algorithms for prime factorization and discrete logarithms on a quantum computer. *SIAM Journal on Computing*, *26*(5), 1484.
https://doi.org/10.1137/S0097539795293172
- Quantum Computing Verstehen – Grundlagen – Anwendungen – Perspektiven (Matthias Homeister) p. 222
https://link.springer.com/book/10.1007/978-3-658-36434-2

**Grover's algorithm**
*Background*: Grover's algorithm is a probabilistic quantum search algorithm that is categorically faster than classical algorithms.
*Areas*: Algorithms, probability theory, database search
*Task*: You learn about probabilistic quantum algorithms, Householder transform, Grover's algorithm and the proof of its asymptotic runtime.
'hands-on' task: You implement Grover's algorithm with a small example dataset that you design by yourself.
*Sources*:
- Grover, L. K. (1996). A fast quantum mechanical algorithm for database search. *Proceedings of the Annual ACM Symposium on Theory of Computing*, *Part F129452*, 212–219.
https://doi.org/10.1145/237814.237866
- Quantum Computing Verstehen – Grundlagen – Anwendungen – Perspektiven (Matthias Homeister) p. 138, https://link.springer.com/book/10.1007/978-3-658-36434-2
- Book by Choi, p. 178: https://link.springer.com/content/pdf/10.1007%2F978-3-030-91214-7.pdf

**Variational quantum eigensolvers**
*Background*: Variational quantum eigensolvers use a variational principle to find the ground state energy of a given Hamiltonian. This is a promising approach to applications especially in condensed matter physics and quantum chemistry.
*Areas*: Applied computational quantum physics and quantum chemistry
*Tasks*: You will learn about fields where finding the ground state function and ground state energy of a Hamiltonian is important, the computational problems of finding these states and the technique of variational quantum eigensolvers to address the problem.
'hands-on' task: You will implement a variational quantum eigensolver and find the ground state

energy of a simple example Hamiltonian.
*Remark:* Advanced topic
*Sources*:
- Tilly, J., Chen, H., Cao, S., Picozzi, D., Setia, K., Li, Y., Grant, E., Wossnig, L., Rungger, I., Booth, G. H., & Tennyson, J. (2021). *The Variational Quantum Eigensolver: a review of methods and best practices*. https://doi.org/10.48550/arxiv.2111.05176

**Majorana surface code**
*Background*: Majorana modes are promising nonabelian anyons for topological quantum computing. They cannot be used for universal topological quantum computing, but there are schemes around this problem, for instance the surface code of this project.
*Areas*: Topological quantum computing, surface codes
*Task*: You will understand Majorana zero modes, that they are nonabelian anyons, and how their fusion and braiding can be used for possibly error-prone quantum computation.
'hands-on' task: You will simulate a small Majorana surface code on a nontopological quantum computer.
*Sources*:
- Vijay, S., Hsieh, T. H., & Fu, L. (2015). Majorana Fermion Surface Code for Universal Quantum Computation. *Phys. Rev. X*, *5*(4), 41038. https://doi.org/10.1103/PhysRevX.5.041038

**Toric code**
*Background*: The toric code is the prime example how anyons can be used for quantum computing and how topological states can help making gates in quantum computing robust.
*Areas*: Topological quantum computing, nonabelian anyons.
*Task*: You understand what anyons are, how they form the degenerate computational subspace, and how braiding and fusing them results in the manipulation of this subspace.
'hands-on' task: You will implement the toric code for very few anyons and their braiding to run on a nontopological quantum computer.
*Sources*:
- Kitaev, A. (2006). Anyons in an exactly solved model and beyond. *Annals of Physics*, *321*(1), 2–111. https://doi.org/10.1016/j.aop.2005.10.005

**Quantum supremacy**
*Background*: Google showed in 2019 that current-day quantum computers can outperform current-day's fastest supercomputers by a large margin when computing specific tasks.
*Areas*: Quantum computing, quantum supremacy
*Task*: You will understand an example for a problem that quantum computers are much more efficient in solving and review the debate about the claimed quantum supremacy by Google.
'hands-on' task: You will reprogram the quantum supremacy problem and simuate/run it on a quantum computer.
*Sources*:
- Arute, F., Arya, K., Babbush, R., Bacon, D., Bardin, J. C., Barends, R., Biswas, R., Boixo, S., Brandao, F. G. S. L., Buell, D. A., Burkett, B., Chen, Y., Chen, Z., Chiaro, B., Collins, R., Courtney, W., Dunsworth, A., Farhi, E., Foxen, B., … Martinis, J. M. (2019). Quantum supremacy using a programmable superconducting processor. *Nature*, *574*(7779), 505–510. https://doi.org/10.1038/s41586-019-1666-5
- IBM's contrapost: https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/

**Quantum hardware for eigenvalue problems**

*Background*: Eigenvalue problems are an elementary important task for physics and engineers. Quantum computers can be used to accelerate solving these problems for large matrices.

*Task*: You understand the problem of finding eigenvalues and eigenstates of a matrix and how quantum computers can help finding these values qualitatively faster than a classical computer. Eigenvalues and vectors have profound importance in, e.g., wave equations, oscillations, quantum mechanics, and numerical optimization.

*Areas*: Eigenvalues of a matrix, mathematics, physics

'hands-on' task: You will implement an algorithm for finding the eigenvalues of a diagonalizable matrix that represents a problem of your choice, e.g., phonon modes, drum modes, and diagonalize small matrices on a quantum computer/simulator.

*Source*s:

- Shao, C. (2019). *Computing eigenvalues of diagonalizable matrices in a quantum computer*. https://doi.org/10.48550/arxiv.1912.08015

**Error correction and stabilizer codes**

*Background*: Quantum error correction is central to make quantum computers capable of delivering reliable results. Small perturbations can already collapse the quantum states of a system, yet, quantum error correction is a way to avoid the influence of noise to a certain extent. It is believed that, because of error correction, quantum computers can work 'perfectly' once the number of qubits is sufficiently large and the error rate per gate is sufficiently low.

*Areas*: Computing, error correction

*Task:* You will understand why quantum error correction is necessary, what it is, and understand the threshold necessary for quantum computers to work error-free.

'hands-on' task: You will implement a simple quantum error correction code of your choice by yourself and simulate and test its real-world error-reduction capabilities.

*Source*s:

- Gottesman, D. (1996). Class of quantum error-correcting codes saturating the quantum Hamming bound. *Physical Review A - Atomic, Molecular, and Optical Physics*, *54*(3), 1862–1868. https://doi.org/10.1103/PhysRevA.54.1862

- A Quantum Computation Workbook (Mahn-Soo Choi) https://link.springer.com/book/10.1007/978-3-030-91214-7

- Quantum Computing Verstehen – Grundlagen – Anwendungen – Perspektiven (Matthias Homeister) https://link.springer.com/book/10.1007/978-3-658-36434-2

**Quantum random walks and its possible applications**

*Background*: Quantum random walks are fundamental processes in nature and the quantum extension of classical random walks, which form the basis of statistical physics, time series prediction and even stock market analysis. They are further important for physical simulations, in particular the (quantum) Monte Carlo method to find out finite-temperature properties of a physical system.

*Areas*: Statistical physics

*Task*: You will understand quantum random walks, their difference and connection to classical random walks and their potential for applications in various fields of physics and other sciences.

'hands-on' task: You will implement a low-dimensional random walk and compare it to a classical

random walk.
*Sources*:
- Quantum Random Walks for Computer Scientists (Salvador Elias Venegas-Andraca) https://ieeexplore.ieee.org/xpl/ebooks/bookPdfWithBanner.jsp?fileName=6812671.pdf&bkn=6812670&pdfType=book

## Experimental aspects

**Quantum chemistry** [Merged with 'Variational quantum eigensolvers']

**Real-time pulse control and parameter control (top-level hardware access)** [2 projects]
*Background*: Despite the general aim of making quantum computing code generally applicable to any quantum computing architecture, quantum computer are, at the end, specific, hardware-dependent machines. As such, controlling the quantum hardware in real time will help tweaking the system and getting out most of it. This project is split in two. One part is about superconducting qubits used in IBM quantum computers, the other about the D-WAVE quantum annealing architecture.
*Areas*: Experimental aspects, real-time control of quantum hardware
*Task:* You will understand the hardware involved in current-day quantum technology and how to manipulate it by using programming commands.
'hands-on' task: You will use top-level programming languages to steer the physical effects, i.e., pulse-control, fields, etc. in the respective quantum hardware and perform 'measurements' of the outcome of your manipulation.
*Sources*: Documentation of the hardware control in Qiskit: https://qiskit.org/ and Leap/Ocear SDK: https://docs.dwavesys.com/docs/latest/leap.html. Official description of the hardware at the vendor's data sheets.

**Artificial noise increase**
*Background*: Environmental noise is ultimately unavoidable and affects quantum computations negatively.
*Areas*: Noise in quantum computation, noisy intermediate scale quantum computing
*Task*: You will simulate random intermediate measurements and additional gate errors during a quantum computation, which you introduce on purpose. You will see how the quantum calculation and simulation gradually breaks down by this.
'hands-on' task: You will introduce extra gate and readout errors and determine their influence on the fidelity of the quantum hardware.
*Sources*: Qiskit noise model and general Qiskit documentation for adding random quantum gates and readouts: https://qiskit.org/

**Experimental detection of gate-errors and noise**
*Background*: Classifying the gate errors and readout errors happening in a quantum computation is essential to understand which accuracy can be expected in a calculation. In this project, you will classify the gate errors that appear in a quantum computation or simulation of such and will compare it to the official stats given by the vendors.
*Areas*: Applied quantum computing
'hands-on' task: You will run tests with the existing quantum hardware or simulation of such to classify the gate and readout errors of the machines.
*Sources*: Documentation of the hardware control in Qiskit: https://qiskit.org/ and Leap/Ocear SDK:

https://docs.dwavesys.com/docs/latest/leap.html. Official description of the hardware at the vendor's data sheets.

### Time crystals

*Background*: On Google quantum computers, researchers have realized states of matter that could have been realized nowhere else so far. One of these states is the time crystal.
*Areas*: Quantum computer as quantum simulator
*Task*: You will understand what a time crystal is and find out why and how exotic states of matter can be simulated on a quantum computer.
'hands-on' task: You will implement the code for simulating a time crystal on a quantum computer.
*Sources*:
Mi, X., Ippoliti, M., Quintana, C., Greene, A., Chen, Z., Gross, J., Arute, F., Arya, K., Atalaya, J., Babbush, R., Bardin, J. C., Basso, J., Bengtsson, A., Bilmes, A., Bourassa, A., Brill, L., Broughton, M., Buckley, B. B., Buell, D. A., … Roushan, P. (2021). *Observation of Time-Crystalline Eigenstate Order on a Quantum Processor*. https://arxiv.org/abs/2107.13571v2
- Frey, P., & Rachel, S. (2021). *Realization of a discrete time crystal on 57 qubits of a quantum computer*. https://doi.org/10.48550/arxiv.2105.06632

## Industrial/economical applications

### Binary optimization on a quantum annealer

*Background*: A quantum annealer uses quantum mechanical effects to solve an optimization problem. In contrast to quantum computers, these machines are not universal, but they contain nowadays a much larger number of qubits (several thousands). They are not categorically faster for problems with worst-case scenarios, but they can be used to solve large-scale optimization problems already today because of the dedicated hardware. Binary quadratic optimization is a primary task for quantum annealers, which is a frequent form industrial optimization problems with binary variables can be casted into.
*Areas*: Quantum annealing, quantum optimization
*Task*: You will understand constrained binary quadratic optimization and see the industrial use cases.
'hands-on' task: You will implement a quadratic binary optimization problem and solve it with a quantum annealer, e.g., linear systems or the Ising Spin model.
*Sources*: DWave documentation https://docs.ocean.dwavesys.com/en/stable/concepts/bqm.html

### Traveling salesman problem on a quantum annealer

*Background*: The traveling salesman problem is a classical problem of 'finding the shortest path'. It is a problem standing for a whole complexity class and many other problems can – more or less unexpectedly – be mapped onto this problem. Quantum annealers are well-suited for solving these optimization problems and implementations readily exist.
*Areas*: Quantum annealing, quantum optimization
*Task:* You will understand the difficulties of the traveling salesman problem, its universality class, and how quantum annealers can be used to solve them.
'hands-on' task: You will implement the traveling salesman problem on an interesting small problem of your choice, e.g., traffic planning in Hamburg, taking the fastest bus trip for visiting several sights, or similar.
*Sources*:

- Jain, S. (2021). Solving the Traveling Salesman Problem on the D-Wave Quantum Computer. *Frontiers in Physics*, *9*, 646. https://doi.org/10.3389/FPHY.2021.760783

**Volkswagen's and DB's applications of quantum annealing and computing** ***Background***
*Areas*: Quantum optimizers like current-day quantum annealers and also noisy intermediate scale quantum computers have caught the attention of large-scale companies to feed their need for large-scale optimization. As an example, Volkswagen and Deutsche Bahn (DB) both run sections dedicated to quantum computing and quantum optimization. This is likely related to optimizing the traffic flow of their public transport systems but also for general future use.
*Task:* Your task is to review the publically available information on selected industrial projects in quantum computing and estimate how realistic they are.
'hands-on' task: You will pick one problem of a call from industry that can be formulated as binary or integer quadratic problem and implement a small-scale solution by a quantum annealer.
*Source*s:
- Official announcements of large-scale companies about quantum computing projects, like Volkswagen: https://www.volkswagenag.com/en/news/stories/2019/11/where-is-the-electron-and-how-many-of-them.html
and DB: https://cambridgequantum.com/cambridge-quantum-deutsche-bahn-partnership/
- DWave documentation of solving quadratic problems
https://docs.dwavesys.com/docs/latest/c_gs_3.html

## General aspects

***Quantum teleportation, encryption, key distribution and the no-cloning theorem**
*Background*: In contrast to classical information, quantum information can be submitted 100% secure, proven, without caveat, based on the no-cloning theorem. This process relies on quantum teleportation, which can by achieved by a number of protocols, and enhanced with encryption and key distribution methods.
*Areas*: Quantum information transfer
*Task:* You will understand how quantum teleportation work and why it is secure based on the no-cloning theorem.
'hands-on' task: You will implement quantum teleportation between different qubits of one quantum computer. If more than one person is working at this project, you will do so using different algorithms for quantum teleportation, encryption, and quantum key distribution.
*Source*s:
- Bennett, C. H., & Brassard, G. (2020). Quantum cryptography: Public key distribution and coin tossing. *Theoretical Computer Science*, *560*(P1), 7–11. https://doi.org/10.1016/j.tcs.2014.05.025
- Ekert, A. K. (1992). *Quantum Cryptography and Bell's Theorem*. 413–418. https://doi.org/10.1007/978-1-4615-3386-3_34
- p.167 of Quantum Computing Verstehen – Grundlagen – Anwendungen – Perspektiven (Matthias Homeister)
https://link.springer.com/book/10.1007/978-3-658-36434-2
-Book chapter by LaPierre:
https://link.springer.com/content/pdf/10.1007%2F978-3-030-69318-3_6.pdf

**Quantum code cracking**
*Background*: In our everyday world, communication is secured by encryption algorithms that rely on

keys and passwords. Quantum computers are said to be capable of cracking such codes, such that original secure communication is no longer possible. This potentially has profound implications, especially for bank transfers and blockchain protocols.
*Areas*: Quantum cryptography
*Task*: You review how safe current-day encryption methods are against quantum computers and quantum annealers and especially understand which encryption techniques remain safe.
*Task:* You implement a key cracking algorithm in a quantum annealer or quantum computer, e.g., the RSA algorithm or simpler
*Remark*: Advanced
*Source*s:
- Gidney, C., & Ekerå, M. (2019). How to factor 2048 bit RSA integers in 8 hours using 20 million noisy qubits. *Quantum*, *5*, 1–31. https://doi.org/10.22331/q-2021-04-15-433
- Bernstein, D. J. (n.d.). *Introduction to post-quantum cryptography*. http://www.pqcrypto.org/www.springer.com/cda/content/document/cda_downloaddocument/9783540887010-c1.pdf

**Topological quantum computing and its simulation: Fibonacci anyon fusion and braiding**
*Background*: Topological quantum computing is a next-generation approach to quantum computing that is followed intensely in research and some large-scale companies.
*Areas*: Topological quantum computing
*Task:* You will understand how ordinary quantum computing code is realized (compiled) efficiently by braiding nonabelian anyons and vice versa.
'hands-on' task: You will encode the braiding of a number of Fibonacci anyons in ordinary quantum code.
*Source*s:
- Kliuchnikov, V., Bocharov, A., & Svore, K. M. (2014). Asymptotically optimal topological quantum compiling. *Physical Review Letters*, *112*(14), 140504. https://doi.org/10.1103/PHYSREVLETT.112.140504

**Quantum annealing and machine learning**
*Prerequisites*: Knowledge on Machine Learning.
*Background*: Quantum computing can assist the training of classical artificial neural networks or even directly change the way we think about machine learning using genuine quantum machine learning. This project focuses on the first part, where a quantum annealer is used to train a neural network and thereby deliver optimal solutions to the networks weights fast.
*Areas*: Machine learning, artificial neural networks, quantum annealers
*Task*: You will learn how machine learning can be assisted by quantum computers and, as a possible extension, learn about genuine quantum mechanical machine learning architectures.
'hands-on' task: You will implement a small artificial neural network to a known task, i.e., a game or a the MNIST hand-written letter test, and optimize its weights using a quantum annealer. You will compare this to classical training of the network.
*Source*s:
- Book 'Quantum Machine Learning: An Applied Approach' (Santanu Ganguly) https://link.springer.com/book/10.1007/978-1-4842-7098-1

*particularly suitable group projects