Example Course Projects

Presentation day: TBD, January 2025
We will organize your presentation based on your availability during the exam period.

Confirmation period: TBD, approximately Oct 28 - Nov 8.
Plan to meet and discuss your choice of project with the Prof. We will probably group the meetings by topics in the interest of time. Often an email discussion does the job.

<u>Rubric: a successfully completed project:</u>

1. Introduces a new topic to fellow students based on book chapters or research/review papers.
2. Contains a bit of independent study in the form of (usually) some code that generates some calculations and plots supporting the presenter's story.
3. Enables the presenter to answer elementary questions arising in the audience on the topic of the presentation.

Presentation time (powerpoint/keynote slides) is 10 min (sharp)
Q&A time 5-10 min (sharp)

Each student must choose, confirm, prepare, and present one topic.

You are welcome to pick any topic of your interest, we will help you to shape it for an appropriate scope and refer you to a reasonable reference material. The list below is just a bunch of topics to set off your imagination!

Quantum oscillators

- Introduce Wigner function for describing the states of a harmonic oscillator. Introduce and relate the Fock states, the coherent states, and the Schrodinger cat states.

- Describe how to measure the Wigner function of an oscillator using a qubit.

Review article on the topic: https://arxiv.org/pdf/1710.03179

- Compare in detail the behaviours of resonantly driven harmonic oscillator with a resonantly driven qubit.

Qutrits and Qudits

- We can encode quantum information not only using 2-level systems but also using 3-level systems (Qutrits) or, more generally, d-level systems (Qudits).

See, for example https://www.nature.com/articles/s41567-022-01658-0

Charge in a uniform magnetic field

- A charged particle in a uniform magnetic field moves around in a circle, so it is kind of an artificial atom, called Geonium. Find its spectrum and compare to other quantum systems you know.

This project requires a little knowledge of electromagnetism (namely, vector potentials, that B = curl (A)). But not more than that.

- People can indeed trap a single (just one!) electron in a solenoid (called Penning trap) and did a number of pioneering quantum demonstrations with it.

See review article https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.58.233

- Microscopic Penning traps are also used in modern quantum technology for building ions-based quantum processors.

https://www.nature.com/articles/s41586-024-07111-x

Atoms and the periodic table

- In atomic physics, the properties of the angular momentum operator are important. Compare it to the more familiar spin-1/2 Pauli operators.

- Spectrum and wave functions of Hydrogen atom. This is a quantum version of the elementary planetary motion problem.
- Chemical properties of atoms in a periodic table can be explained from the properties of the Hydrogen atom, by making the nucleus heavier and adding more electrons to occupy the quantum orbitals.

Under-barrier tunneling

- Model the quantum tunneling effect on energy levels and wave functions of a particle in a double-well potential.
- How much time it takes for a particle tunnel across a potential barrier?

https://journals.aps.org/rmp/abstract/10.1103/RevModPhys.66.217

Supersymmetric quantum mechanics

- In case you want to do feel like a string theorists (it's not that hard), study the supersymmetric formulation of quantum mechanics, apply it to harmonic oscillator and some other problem:

https://arxiv.org/pdf/0910.0192

Many-body dynamics

- Model a system of N qubits coupled to each other by the *Ising* Hamiltonian (1D or 2D)
- Study the lowest energy states at weak coupling, far away from the critical point [spin waves]
- Study the lowest energy states at critical coupling [the quantum phase transition]. How entangled are they?
- Show the exponential difficulty of solving for the energy states as you increasing N.

- Efficient representation of quantum states: some quantum states of N qubits require a lot less than 2^N basis states to describe what's going on. In this case there are methods to solve for the lowest energy eigenvalues of the Hamiltonian using Matrix Product States; PEPS; Tensor Product Methods. Learn about some of that and apply to a simple system (such as N-qubit chain spectrum).

There are tools in QuTiP to simulate coupled qubit chains, check them out.

Dissipation in quantum mechanics

- Linbladt master equation. There is an equation, not a Schrodinger's equation, which allows us to model energy relaxation & dephasing processes in a qubit.

https://arxiv.org/pdf/2312.13214 (pedagogical intro)

- Model dephasing and relaxation in an ideal qubit coupled to an oscillator, which is coupled to a thermal bath. These are the key decoherence mechanisms in a quantum computing experiment.

- Two-photon loss in an oscillator. Solve for the dissipative dynamics of an oscillator due to a weird thermal bath: an oscillator can only loose 2 photons at a time, but never one. See an experimental implementation here https://www.science.org/doi/abs/10.1126/science.aaa2085

Quantum trajectory theory

There is a way to simulate the act of measurement which collapses the quantum superposition onto one of the measurement outcomes. https://en.wikipedia.org/wiki/Quantum_Trajectory_Theory

Quantum technology platforms

Pick one hardware platforms for quantum information processing and learn as much as you can about it:

- Atomic clocks (qubit transition/cycling transition/sync/limitations)
- Trapped ion quantum computing
- Rydberg atom quantum computing
- Superconducting qubit quantum computing [artificial circuit atoms]
- Measurement based QC, photonics

- Adiabatic QC, quantum annealing

Quantum algorithms

- Explain Deutch algorithm or any of its derivatives.
- Explain other simple algorithm of your choice.

Quantum communication

- Bell Inequalities (describe any recent experiment on the topic)
- CHSH test
- Mermin 3 qubit test
- Experiments on Loophole-free Bell tests
- Contextuality in quantum mechanics; 'magic states'
- Quantum cryptography, BB84 protocol.
- Quantum cryptography NOT based on entanglement:

`Quantum cryptography based on Bell's theorem', Artur K. Ekert, Phys. Rev. Lett. 67, 661 (1991).
'Quantum Cryptography: Public Key Distribution and Coin Tossing,' Charles H. Bennett and Gilles Brassard, arxiv.org/abs/2003.06557.
'Entanglement-based quantum communication over 144km,' R. Ursin et al. (Zeilinger group), doi:10.1038/nphys629

Tomography & Benchmarking

Learn about ways to characterise a quantum state and a quantum process (a gate)

- Randomized benchmarking
- Cross-entropy benchmarking
- Gate-set tomography

Quantum control techniques

- Dynamical decoupling: CPMG protocol to cancel slow time-fluctuations of qubit frequency
- DRAG protocol to suppress leakage outside the computational space in transmon qubits

Trotterization

- Learn how to use only single-qubit and two-qubit gates to model the dynamics of any Hamiltonian using the Trotter decomposition.

Quantum error correction

- Describe the 5-qubit Stean code
- Describe the surface code
- Any other quantum error correcting code you wish to present!

Quantum random number generation

- Study the design of a commercial quantum random number generator. Compare performance to a classical one.

Note: this topic seems to be popular among students, it seems deceivingly simple. However, it is very easy to generate hard questions on this topic, so think twice if you really-really want to study QRNG over anything else in this list!

Two-qubit gate schemes (pairs)

iSWAP (tune frequencies in resonance)
iSWAP (drive a 2-photon transition)
iSWAP (drive another 2-photon transition)

Adiabatic CZ via non-computational repulsion (tune frequency)
Non-adiabatic CZ bias temporary full excitation (tune frequency)

Microwave activated gate
Cross-resonance gate

Parametrically activated gates

Two-qubit gate schemes in multi-qubit systems

Quantum bus
Molmer-Sorensen gate via collective modes

ANY OTHER TOPIC YOU WISH TO COVER!