CS-308: Introduction to Quantum Computation

Teacher: Thomas Vidick

Teaching Assistants: Itammar Steinberg & Petia Arabadjieva

Student Assistants: Giovanni Ranieri & Alexandra Golay

Introduction to quantum computing

Quantum Mechanics: A set of physical laws governing systems at the atomic scale and below: $\lesssim 10^{-10}\ m$

- Modern transistors are a few nanometers ($10^{-9}\ m$) wide!

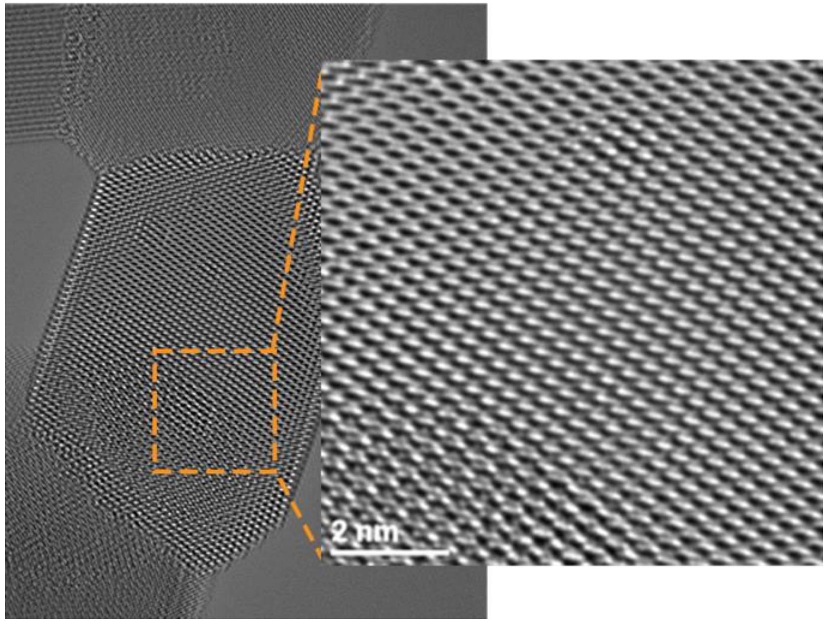
- For a time-scale of a clock signal (taken here as $1\ ns$),

	Frequency	Energy difference in transition between transistor states
Scale for modern (Classical) computers	$1\ GHz$	$\sim 10^{-15}\ J$
Scale for quantum effects to take place	$1\ GHz$	$\sim 10^{-26}\ J$

$\Rightarrow$ Scaling computers down, we must take quantum effects into consideration!

Historical overview

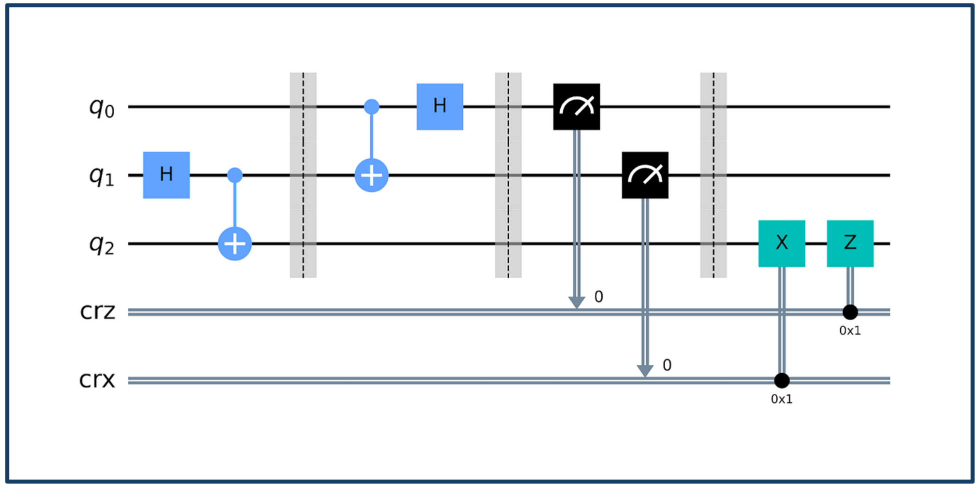
- <u>60's:</u> Richard Feynman. "There's plenty of room at the bottom"
  - *Simulation:* computers that rely on quantum mechanics can help *simulate* quantum systems (e.g., chemical synthesis)
  - *Acceleration:* Use quantum principles to carry out computation more *efficiently* (the emphasis of this course)
  - The scaling problem of quantum computation:
    The full description of an n-particle system scales like $\exp(n)$ in size…
    That is a part of the reason chemical synthesis is hard!



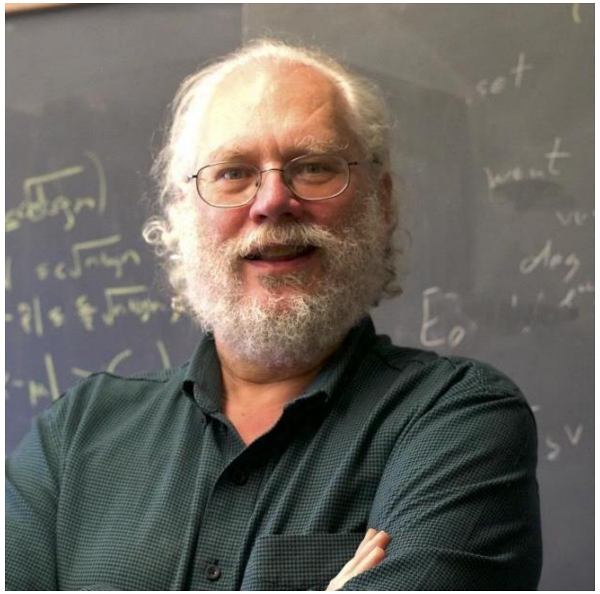
An electron microscope image showing atomic resolution. Nanoscience Instruments

Historical overview

- <u>80’s:</u> Bennett, Wiesner, Deutsch: The formalism of quantum circuits



- <u>90’s:</u> Quantum algorithms (Deutsch-Josza, Bernstein-Vazirani, Grover, Shor)

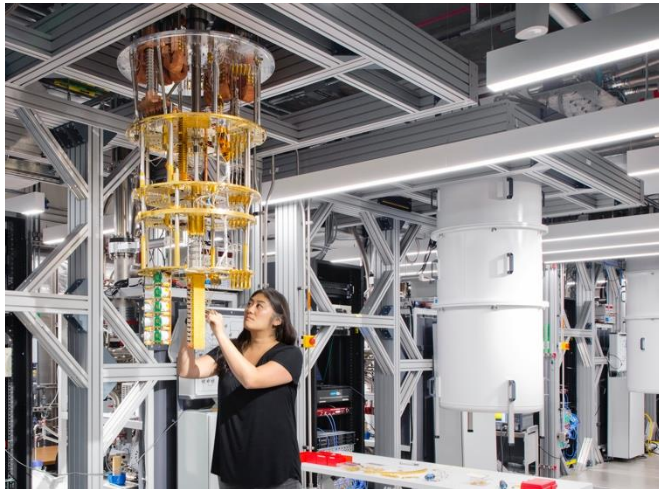


Peter Shor, EP Newsletter

Realisations of Quantum Computers (2000's)

There exist many different ways of realising a quantum computer, each with their own advantages and drawbacks.

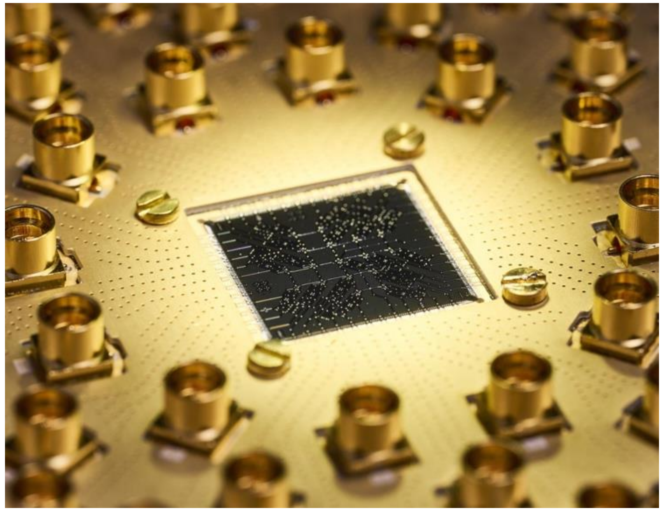
Dilution Refrigerator



IBM Quantum

= Cryogenic setup for cooling down solid state qubits

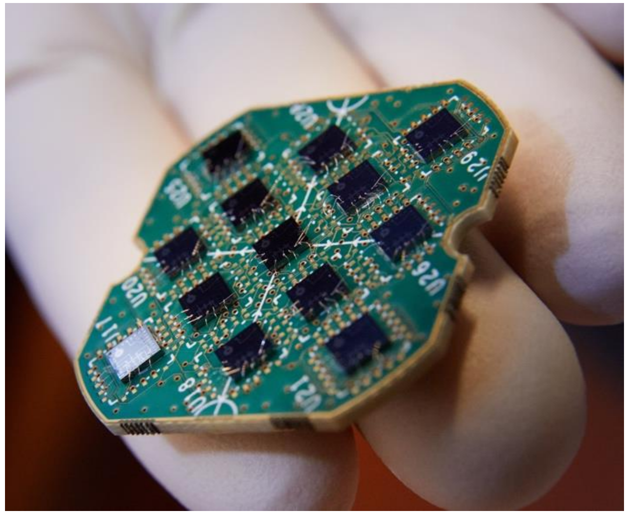
Superconducting Circuits



Quantum Device Lab, ETH Zurich

Record: ~ 1000 qubits (IBM)

Spin Qubits

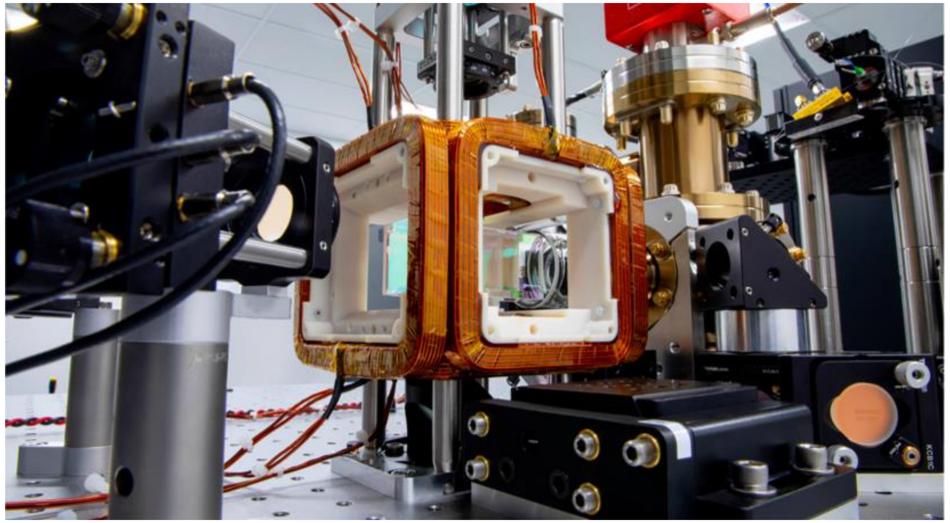


QuTech

Record: ~ 10 qubits [JYvS+25]

Realisations of Quantum Computers (2000's)

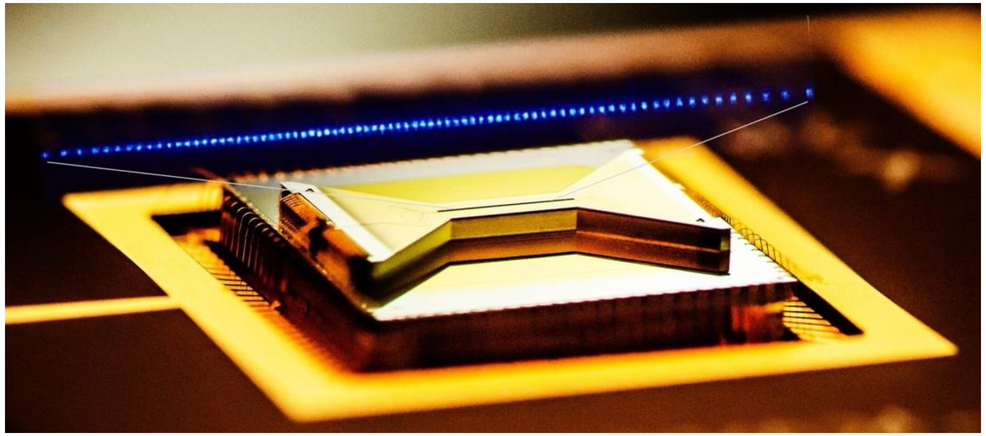
Neutral Atoms



QuEra

Record: ~ 6000 qubits [MNB+25]

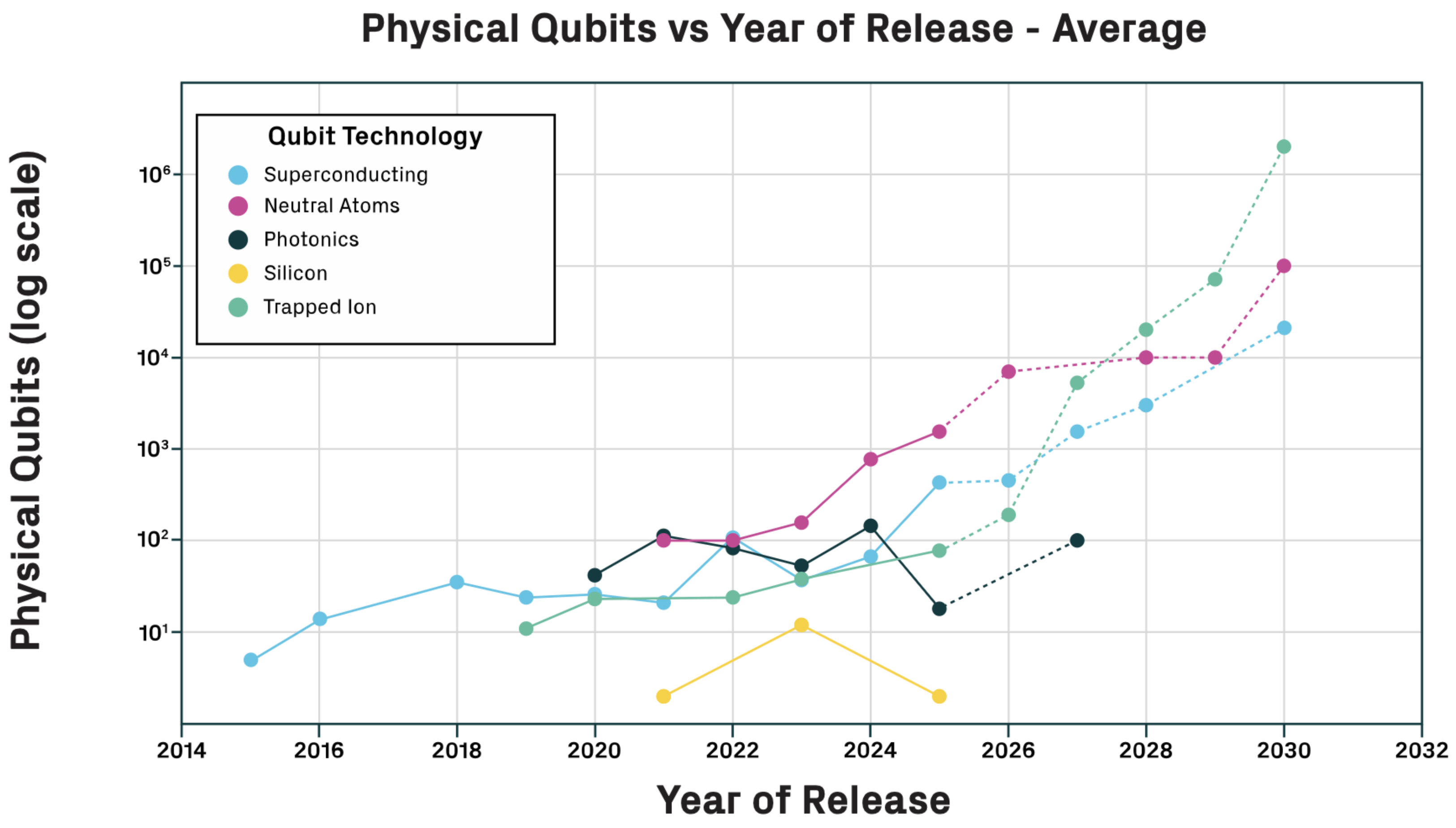
Trapped Ions



Lab of Prof. Christopher Monroe, Duke University

Record: ~100 qubits [RAA+25]

Progress is fast!



Riverlane – QEC Report 2025

Realisations of Quantum Computers

However, performance not determined by number of physical qubits alone!

Key limiting factor: **Errors introduced by external noise** (e.g. heat, mechanical vibrations, control imperfections)

- Solution: **Quantum Error Correction** (Part III of this course)
- Idea: Encode one logical (effective) qubit using many imperfect physical qubits
- For this to work, need low enough error rate (roughly)
- Record number of logical qubits: ? (depending on definition: 0-40)
- Number of logical qubits required to break RSA-2048: 1730 [CFS24]

Course Content

Introduction to quantum computation: mathematical formalism, quantum bits, gates & circuit model

Basic algorithms: Deutsch and Josza's problem and algorithm, Simon's algorithm, Quantum Fourier transform, Shor's factoring algorithm, Grover's search algorithm

Quantum error correcting codes: Models of noise and errors, formalism of stabiliser codes, examples for error correcting codes (Shor, Steane, CSS)

Goals of the Course

- Understand the concept of quantum algorithm in the quantum circuit model
- Describe and analyse basic quantum algorithms
- Implement code for quantum algorithms and run them on real quantum hardware
- Give an example of an error correcting code

Math Prerequisites

Mathematically oriented course, requires high degree of comfort with:

- **Complex Numbers**
- **Linear Algebra** (eigenvectors & eigenvalues, Unitary/Hermitian matrices)
- **Basic Probability Theory**

Don't worry, we will give recaps throughout the lectures, exercise classes and exercise sheets.

It is very important that you build a strong mathematical foundation early on!

Other prerequisite: **Basic knowledge of Python**

Organisation and Grading

- **Lectures**: Wednesdays 9:15-12:00
- **Exercise Classes:** Wednesdays 12:15-13:00, format to be determined by in-class poll
- **Exercise Sheets**: theory & coding exercises, weekly (not graded)
- **Grading**: midterm exam 3/12 , coding-based project 2/12, 7/12 final exam.

Material

- **Moodle**: Announcements, weekly exercise sheets, lecture notes
- **EdForum**: For discussions/questions (link in moodle)
- Other references: **Nielsen & Chuang**, *Quantum Computation and Quantum Information*, Cambridge university Press, 2010.

Coding Project

- **Task**: Implement a quantum algorithm using Qiskit (Python package for quantum computation) and run it on real quantum hardware
- **Preparation**: Qiskit tutorial (more information at later point) & small coding exercises in weekly exercise sheets

References

Theory

[CFS24] *Reducing the Number of Qubits in Quantum Factoring* by Clémence Chevignard, Pierre-Alain Fouque, André Schrottenloher (2024)

Experimental

[MNB+25] *A tweezer array with 6,100 highly coherent atomic qubits* by Hannah J. Manetsch, Gyohei Nomura, Elie Bataille et al. (2025)

[RAA+25] *Helios: A 98-qubit trapped-ion quantum computer* by Anthony Ransford, M.S. Allman, Jake Arkinstall et al. (2025)

[JYvS+25] *Robust and localised control of a 10-spin qubit array in germanium* by Valentin John, Cécile X. Yu, Barnaby van Straaten et al. (2025)

Plan for rest of today

- Linear Algebra Recap
  - Hilbert Spaces
  - Unitary and Hermitian Operators
  - Spectral decomposition
- Linear Algebra in Dirac's Notation
- Tensor Product Space