Quantum Computing: Quick introduction (to a quick introductory course)

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What are you letting yourselves in for?

First 5 weeks or so - A not very advanced introduction to quantum computing from me.

- Quantum mechanics
- Quantum circuit model of quantum computing
- Party tricks - dense coding, teleportation.......
- Quantum advantage - Deutsch's algorithm
- Finding a needle in a haystack - Grover's algorithm
- Breaking the code - Shor's algorithm

Second 5 weeks - more interesting stuff from Matias Ruiz speaking, from afar, after this.

Our Mission, should we choose to accept it...

Understanding how to "read" quantum circuits and bra/ket notation, such as....

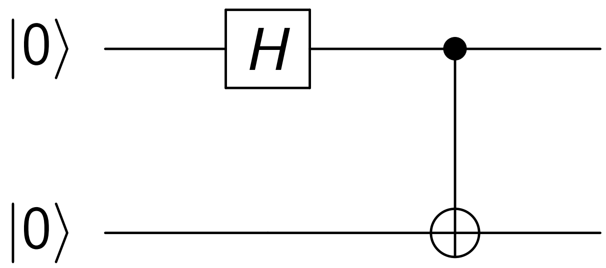


Figure: Quantum circuit for preparing the Bell state $|\psi^{00}\rangle$

Step 1

$$H \otimes I\,|00\rangle = (H\,|0\rangle) \otimes (I\,|0\rangle) = \left(\frac{|0\rangle + |1\rangle}{\sqrt{2}}\right) \otimes |0\rangle = \frac{1}{\sqrt{2}}(|00\rangle + |10\rangle).$$

Step 2

$$\mathrm{CNOT}_{12}\left(\frac{1}{\sqrt{2}}(|00\rangle + |10\rangle)\right) = \frac{1}{\sqrt{2}}(|00\rangle + |11\rangle) = |\psi^{00}\rangle$$

Do Quantum party tricks

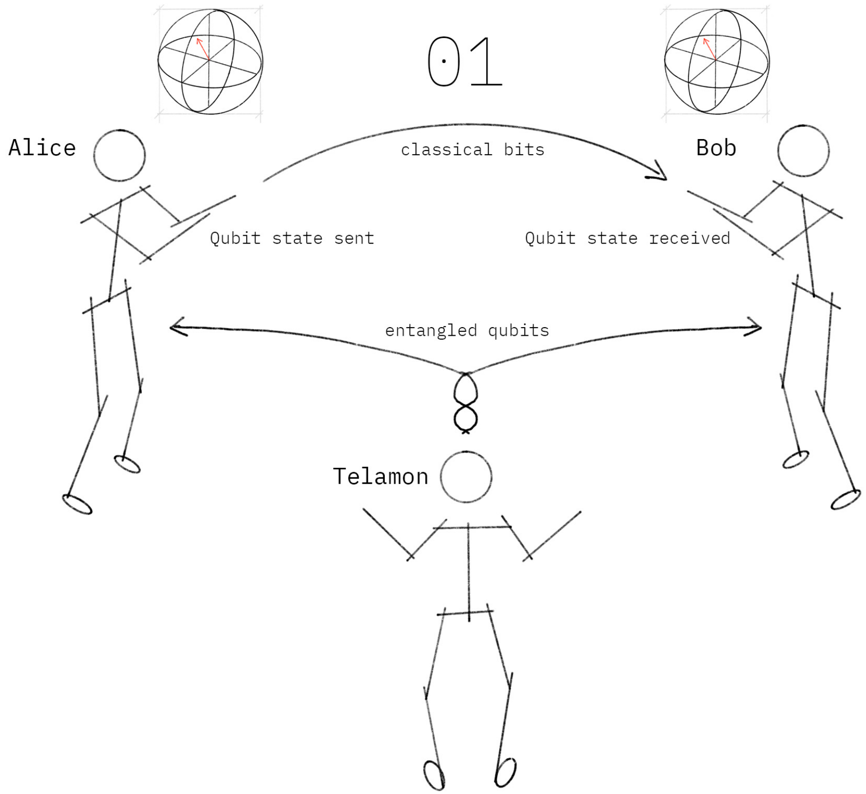
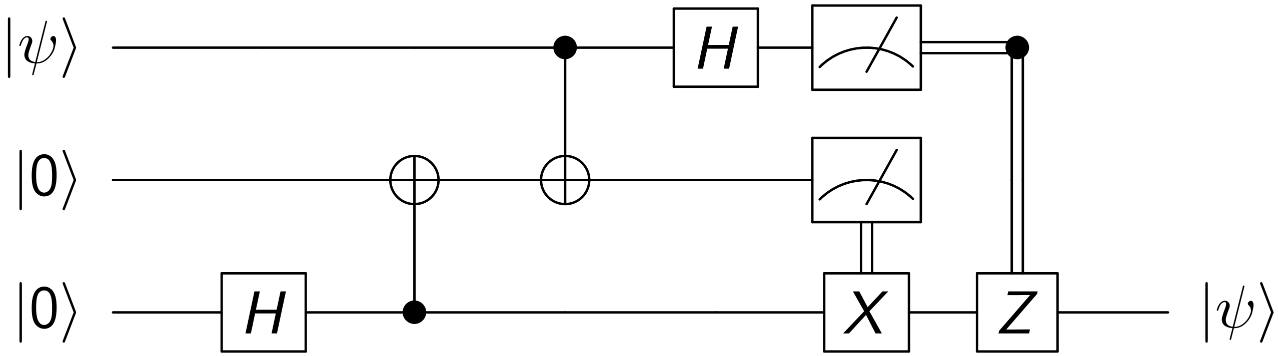


Figure: Alice teleports a state to Bob

Teleportation - Circuit



We might even factor 15 using Shor's algorithm

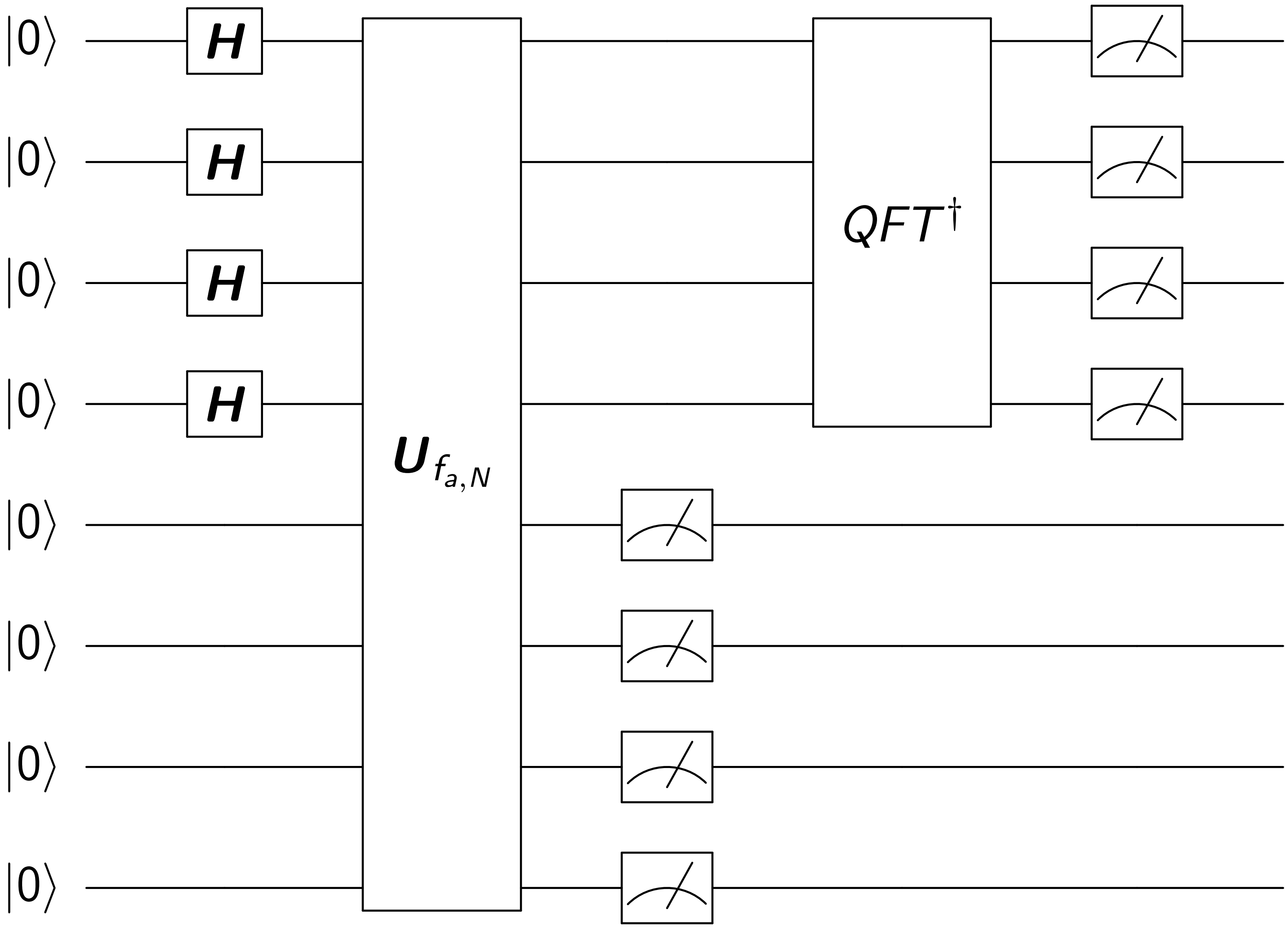


Figure: Factor 15 (5,3)

Second Half: applications of quantum computing

Last 5 weeks – two topics (broadly speaking):

- (3/3.5 lectures) Some cool applications of what you'd have learned with Des:
  - Solving PDEs
  - Simulating molecules
  - Optimisation
  - Machine learning
- (1.5/2 lectures) Adiabatic quantum computing: another paradigm in quantum computing

How to solve PDEs using a quantum computer?

- **The HHL algorithm**: solve

$$Ax = b$$

- **Simulate a quantum system** $\Rightarrow$ solve the Schrodinger equation

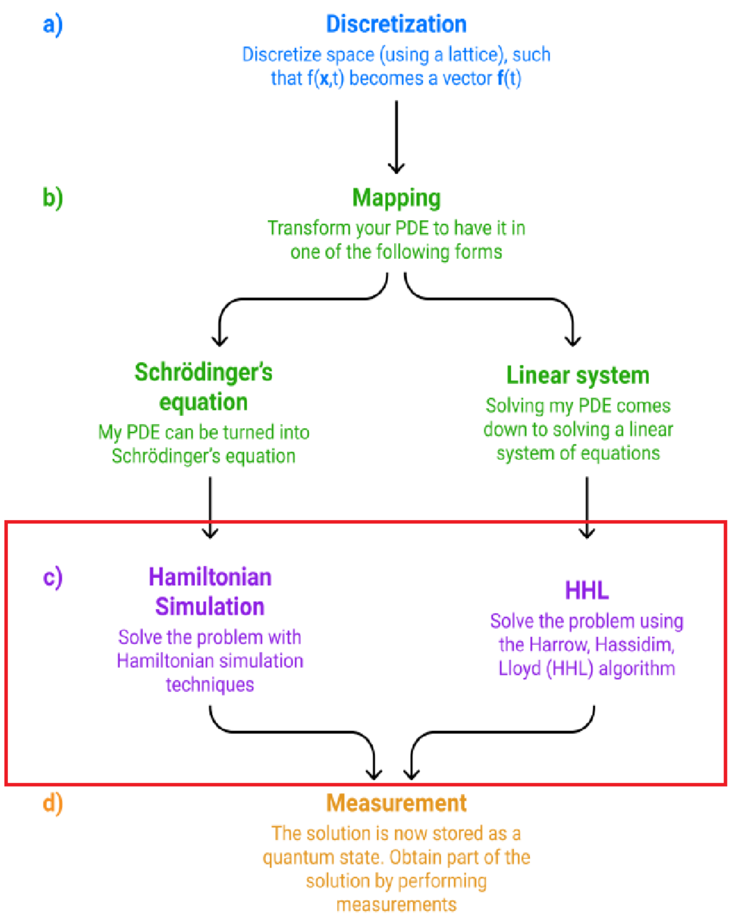


Figure: [A. Pesah, 2020]

Variational Quantum Algorithms – very popular

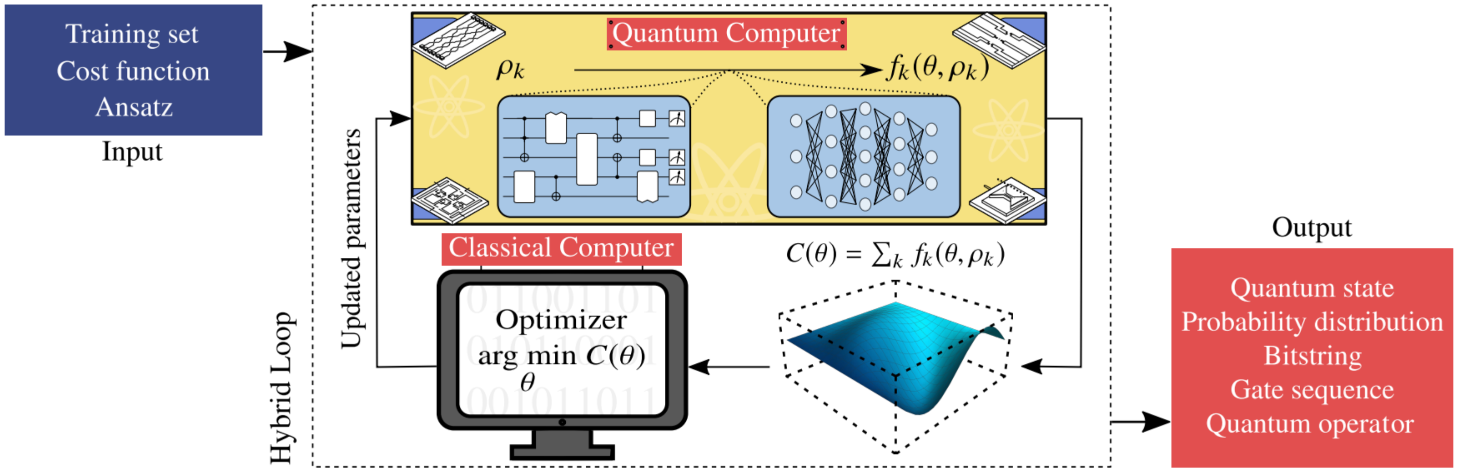


Figure: [Cerezo et al. 2021]

- Find eigenvalues: Variational Quantum Eigensolver (**VQE**) $\Rightarrow$ Simulate molecules in computational chemistry
- **QAOA**: a quantum combinatorial optimisation algorithm

Quantum computing for data science and machine learning

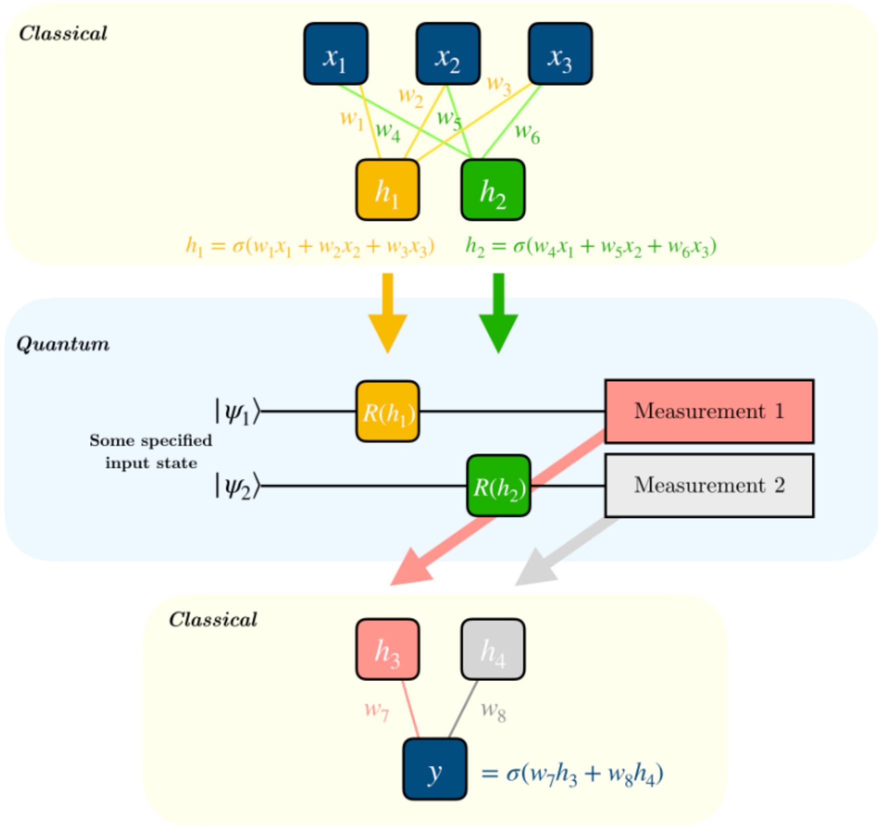
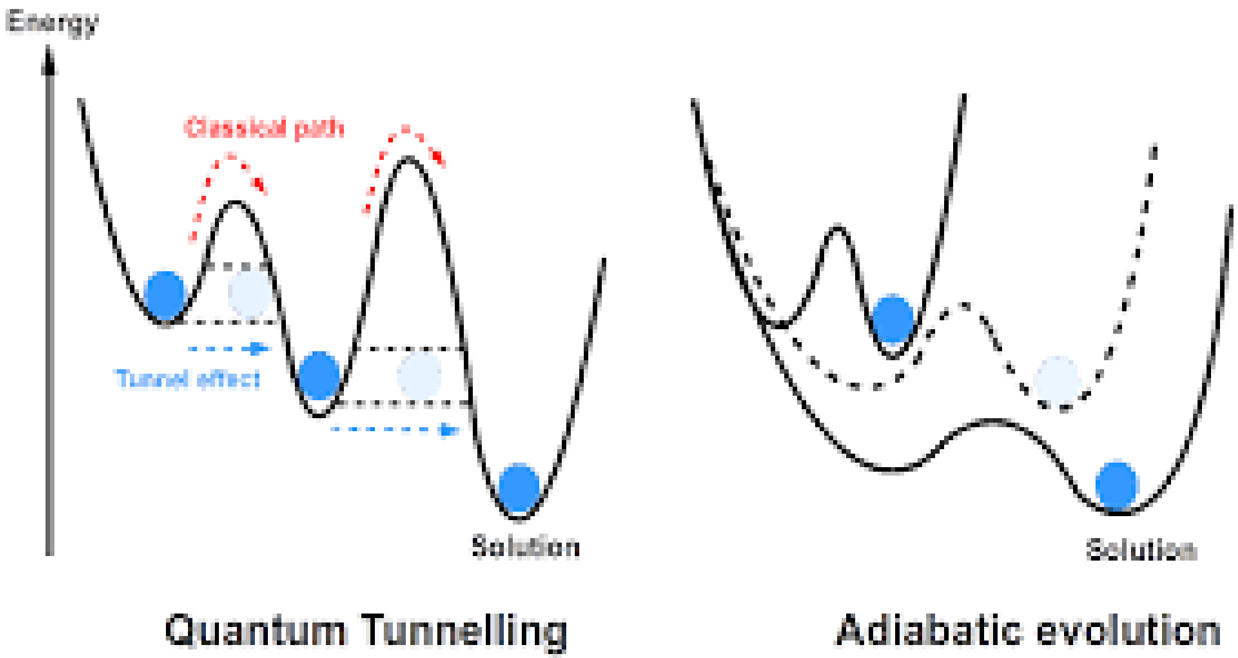


Figure: https://qiskit.org/ (09-2022)

- Many quantum equivalent of standard ML algorithms: quantum PCA, quantum SVM and others

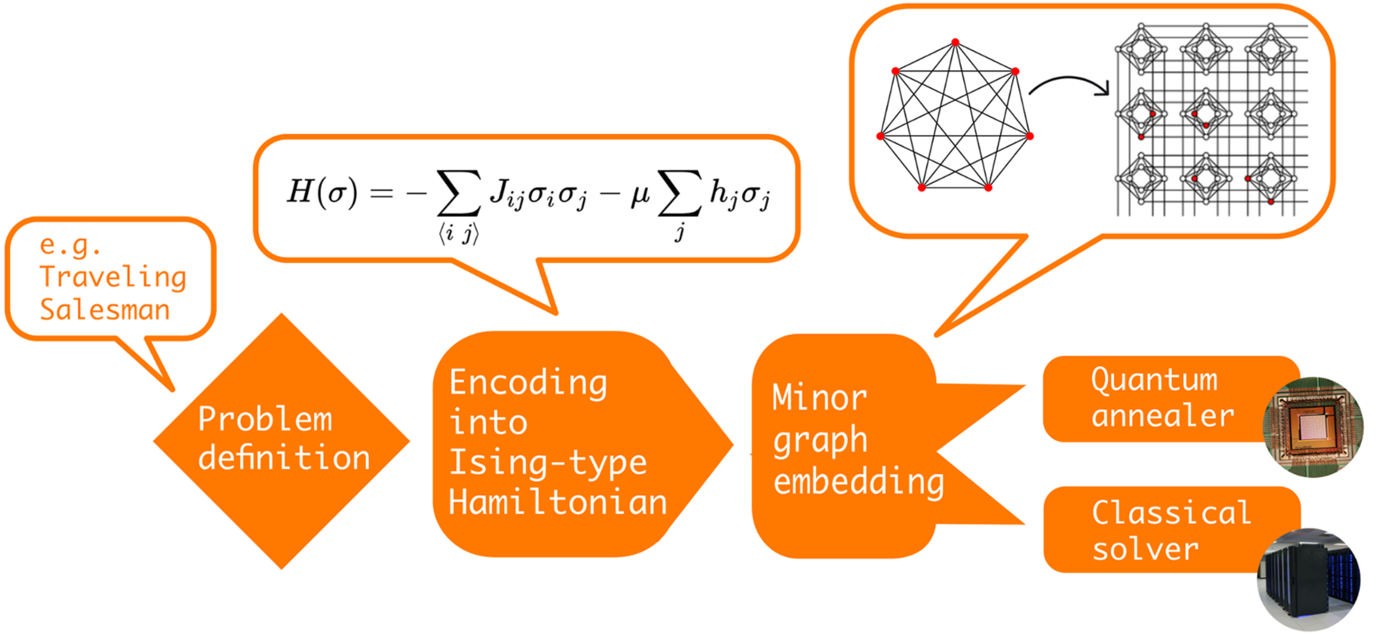
Quantum Adiabatic Computing

$$H(t) = (1 - t)H_0 + tH_p$$

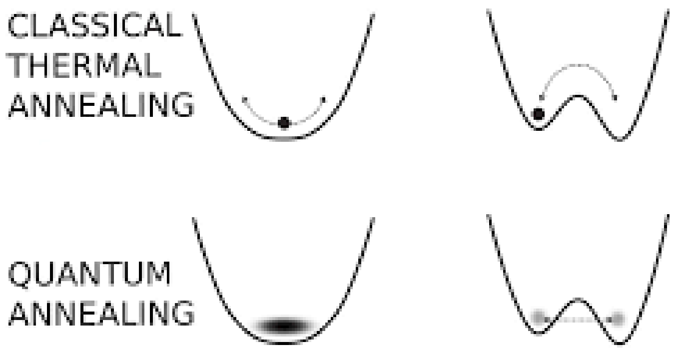


[cite someone]

Quantum annealing: quantum computers for combinatorial optimisation (and maybe more)



[Fingerhuth et al. (2018)]



[Johnson et al. (2011)]

Overview

8 weeks		2 weeks
Gate-based		**Quantum Adiabatic Computing**

Foundamentals:
- Quantum mechanics
  - principles
  - braket notation
  - single and multiple qbits
- Party tricks: dense coding and teleporation
- Deutsch's algorithm
- Grover's algorithm
- Quantum phase and QFT
- Shor's algorithm

Applications:
- HHL algoithm
- Quantum simulations
- Variational Quantum Algorithms
  - VQE
  - QAOA
- Quantum Computing in Data Science
  - Quantum PCA
  - Quantum SVM
  - Quantum NNs

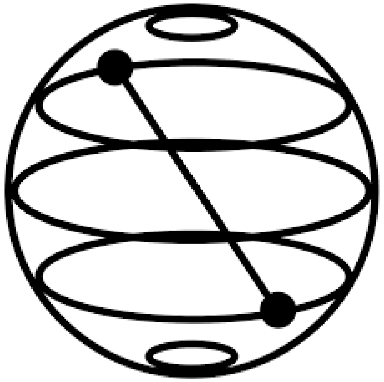
Quantum Adiabatic Computing
- Quantum Adiabatic Theorem
- Quantum Adiabtic Algorithms
- Iising Model and QUBO
- Quantum Annealing

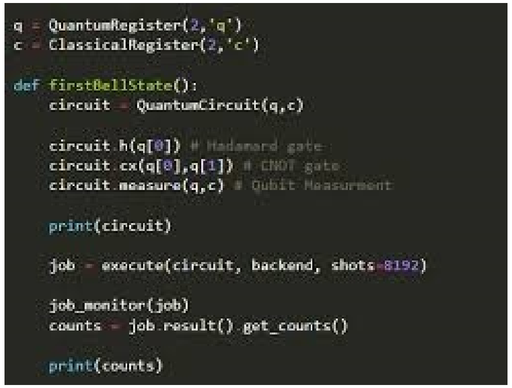
Evaluation

Compulsory for students taking credits on this course.

- Written assignment
- Jypiter notebook assignment to introduce you to Qiskit (what is that? in a minute)
- Small presentation (possibly in groups, depending on number of people taking the class) on a research paper, a topic not (fully) covered during the course, or a given quantum algorithm (that could find in the Quantum Algorithm Zoo; what is that? in a minute).

Useful Resources I: **online**





Qiskit: online open source open development kit for coding quantum algorithms in Python (and which does a **much** better job of explaining things than we ever will)

https://qiskit.org

Play with simulators, online and downloadable, and even real (but not very big) quantum computers.

Useful Resources I: **online**

Quantum Algorithm Zoo

This is a comprehensive catalog of quantum algorithms. If you notice any errors or omissions, please email me at stephen.jordan@microsoft.com. (Alternatively, you may submit a pull request to the repository on github.) Your help is appreciated and will be acknowledged.

Algebraic and Number Theoretic Algorithms

Algorithm: Factoring
Speedup: Superpolynomial
Description: Given an n-bit integer, find the prime factorization. The quantum algorithm of Peter Shor solves this in $\widetilde{O}(n^3)$ time [82,125]. The fastest known classical algorithm for integer factorization is the general number field sieve, which is believed to run in time $2^{\widetilde{O}(n^{1/3})}$. The best rigorously proven upper bound on the classical complexity of factoring is $O(2^{n/4+o(1)})$ via the Pollard-Strassen algorithm [252, 362]. Shor's factoring algorithm breaks RSA public-key encryption and the closely related quantum algorithms for discrete logarithms break the DSA and ECDSA digital signature schemes and the Diffie-Hellman key-exchange protocol. A quantum algorithm even faster than Shor's for the special case of factoring “semiprimes”, which are widely used in cryptography, is given in [271]. If small factors exist, Shor's algorithm can be beaten by a quantum algorithm using Grover search to speed up the elliptic curve factorization method [366]. Additional optimized versions of Shor's algorithm are given in [384, 386]. There are proposed classical public-key cryptosystems not believed to be broken by quantum algorithms, *cf.* [248]. At the core of Shor's factoring algorithm is order finding, which can be reduced to the Abelian hidden subgroup problem, which is solved using the quantum

Navigation

Translations

This page has been translated into:
Japanese
Chinese

Other Surveys

For overviews of quantum algorithms I

Nielsen and Chuang

https://quantumalgorithmzoo.org/

Useful resources II: **ArXiv** and other research papers

Quantum computing from a mathematical perspective: a description of the quantum circuit model by J. Ossorio-Castill and José M. Tornero

https://arxiv.org/abs/1810.08277

Quantum Algorithm Implementations for Beginners by 20 million authors

https://arxiv.org/abs/1804.03719

(which we will both shamelessly plagiarize, along with Qiskit)

Adiabatic Quantum Computing by Albash and others

https://arxiv.org/abs/1611.04471

...and other research papers to be provided in due time

Useful resources III: **Books**

Quantum Computation and Quantum Information by Michael A. Nielsen and Isaac L. Chuang

Quantum Computer Science: An Introduction by N. David Mermin

Mathematics of quantum computing: An Introduction by Wolfgang Scherer