Week 12

Lecture 23

Quantum Computing architectures and quantum complexity classes

Lecture 24

Quantum Computing Review

Lab 12

HHL algorithm using the QUI

Quantum Computing Implementations and Complexity Classes

Lecture 23

Implementations

Different Quantum Computing Hardware

Different ways to implement a quantum computer:

- Ion Traps
- Superconducting qubits
- NV centres
- Quantum Optics
- Semiconductors: Donors and Dots

Ion Traps

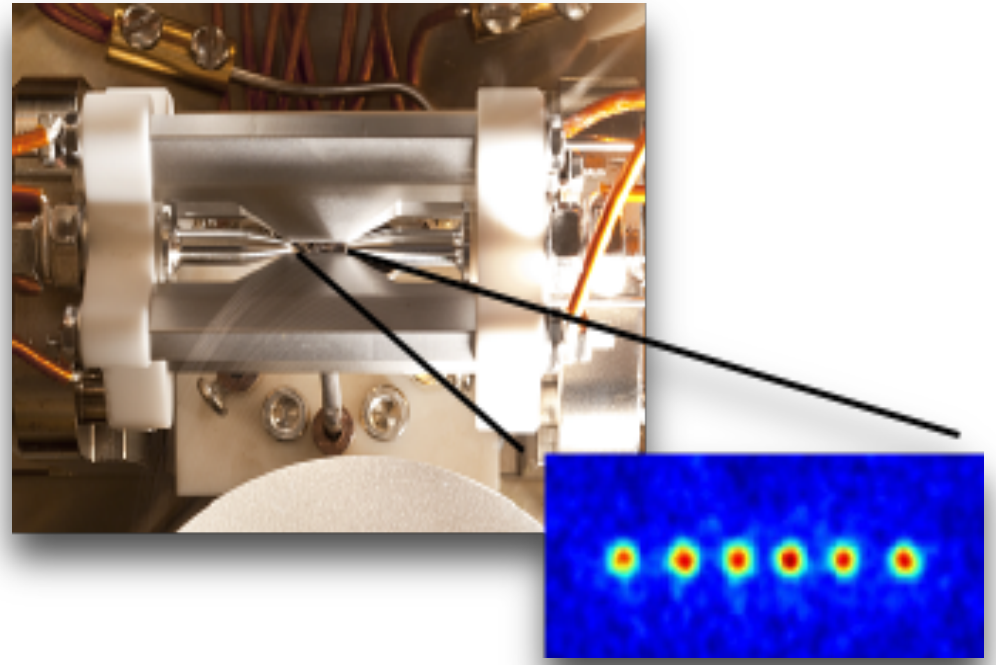


Image: Rainer Blatt (Innsbruck). Electrodes to trap six ^{40}Ca ions. Ions are laser cooled, and can remain in the trap for days once cooled. Qubit manipulation and readout via laser, CCD camera.

Ion Traps (2)

The Qubit: Quantum states of trapped ions (typically ^{40}Ca), interacting via coupling to collective degree of freedom.

Number of Qubits Demonstrated: ~20-50

Fidelity reported: 99.9%

Pros:

- Largest number of high fidelity qubits
- Extremely high fidelity
- Demonstrated error correction code (7 qubit) and largest “genuine” demonstration of Shor’s algorithm. Fault Tolerant QEC demonstration.

Challenges:

- Transport of qubits
- Comparatively large, slow
- Heating

Corportate support

IonQ, Alpine

Paper on measured error rates for ion traps

PHYSICAL REVIEW LETTERS **123,** 110503 (2019)

Probing Qubit Memory Errors at the Part-per-Million Level

M. A. Sepiol, A. C. Hughes, J. E. Tarlton, D. P. Nadlinger, T. G. Ballance, C. J. Ballance, T. P. Harty, A. M. Steane, J. F. Goodwin,* and D. M. Lucas
Department of Physics, University of Oxford, Clarendon Laboratory, Parks Road, Oxford OX1 3PU, United Kingdom

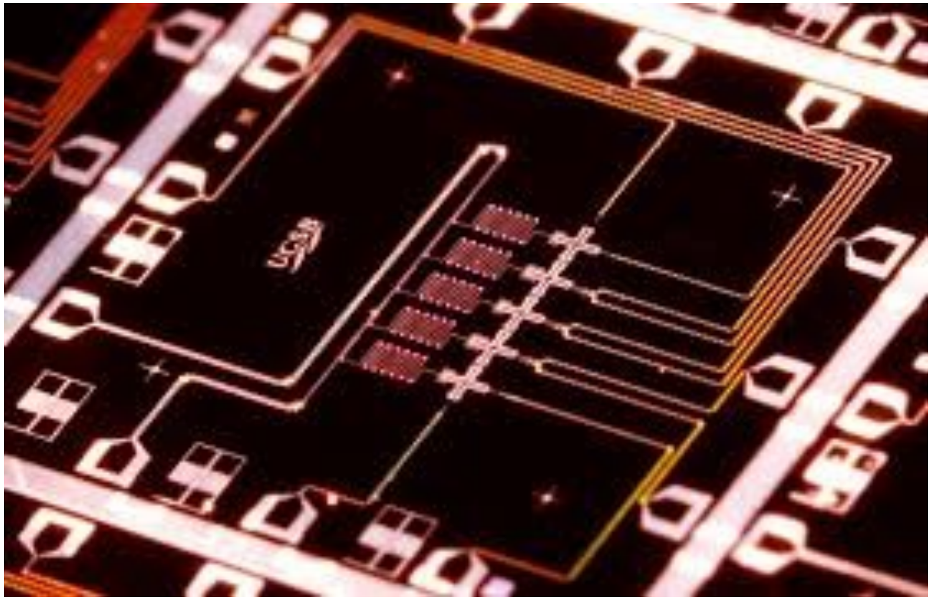
(Received 10 June 2019; published 13 September 2019)

Robust qubit memory is essential for quantum computing, both for near-term devices operating without error correction, and for the long-term goal of a fault-tolerant processor. We directly measure the memory error ϵ_m for a $^{43}Ca^+$ trapped-ion qubit in the small-error regime and find $\epsilon_m < 10^{-4}$ for storage times $t \lesssim 50$ ms. This exceeds gate or measurement times by three orders of magnitude. Using randomized benchmarking, at $t = 1$ ms we measure $\epsilon_m = 1.2(7) \times 10^{-6}$, around ten times smaller than that extrapolated from the T_2^* time, and limited by instability of the atomic clock reference used to benchmark the qubit.

DOI: 10.1103/PhysRevLett.123.110503

Sepiol et al, PRL, 123, 110503, (2019)

Superconducting Qubits



John Martinis (UCSB) Showing five (transmon or Xmon) superconducting qubits placed in a row, each coupled to their neighbour. Information is stored in the charge/phase degrees of freedom.

Superconducting Qubits (2)

The Qubit: The charge or phase degrees of freedom of superconducting circuits. Modern designs (transmon qubits) minimize noise.

Number of Qubits Demonstrated: ~50+

Fidelity reported: 99.4%

Pros:
- Large number of qubits
- Demonstrated transport
- Demonstrated genuine error supression in five and nine qubit error correction codes

Challenges:
- Comparatively fast decoherence times
- Currently comparately large

Corportate support
Google, IBM, Rigetti

Quantum supremacy

Quantum supremacy using a programmable superconducting processor

Google AI Quantum and collaborators†

The tantalizing promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor. A fundamental challenge is to build a high-fidelity processor capable of running quantum algorithms in an exponentially large computational space. Here, we report using a processor with programmable superconducting qubits to create quantum states on 53 qubits, occupying a state space $2^{53} \sim 10^{16}$. Measurements from repeated experiments sample the corresponding probability distribution, which we verify using classical simulations. While our processor takes about 200 seconds to sample one instance of the quantum circuit 1 million times, a state-of-the-art supercomputer would require approximately 10,000 years to perform the equivalent task. This dramatic speedup relative to all known classical algorithms provides an experimental realization of quantum supremacy on a computational task and heralds the advent of a much-anticipated computing paradigm.

In the early 1980s, Richard Feynman proposed that a quantum computer would be an effective tool to solve problems in physics and chemistry, as it is exponentially costly to simulate large quantum systems with classical computers [1]. Realizing Feynman's vision poses signifi-

A COMPUTATIONAL TASK TO DEMONSTRATE QUANTUM SUPREMACY

To demonstrate quantum supremacy, we compare our quantum processor against state-of-the-art classical computers in the task of sampling the output of a pseudo-

Google's quantum supremacy paper, September 20, 2019

Quantum Optics

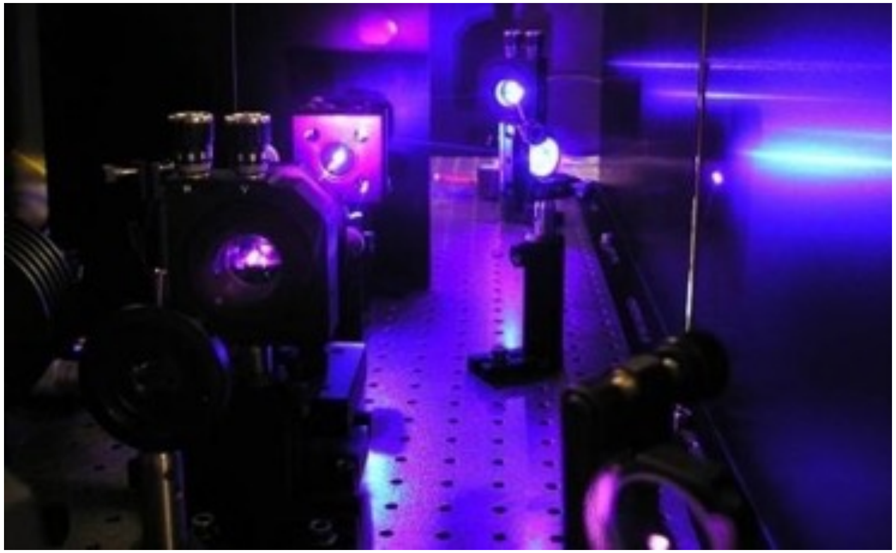


Image from Pryde (Griffiths University). Quantum states of light are used to represent quantum information, and manipulated using linear optics. First proposed by KLM, using entanglement generated by non-linear crystals, and subsequent linear optical operation.

Linear Optics (2)

The Qubit: The optical quantum states of light, including continuous variables, squeezed states, polarization and presence or absence of photons.

Pros:

- Communications and telecommunication applications
- Qubits impervious to their environment
- May demonstrate quantum advantage with Boson sampling

Challenges:

- Interacting large numbers of qubits
- Creating large quantum states
- Single photon sources

Generation of multi-qubit cluster states

SHARE

REPORT

Generation of time-domain-multiplexed two-dimensional cluster state

Warit Asavanant[1], Yu Shiozawa[1], Shota Yokoyama[2], Baramee Charoensombutamon[1], Hiroki Emura[1], Rafael N. Alexander[3], S...

+ See all authors and affiliations

Science 18 Oct 2019:
Vol. 366, Issue 6463, pp. 373-376
DOI: 10.1126/science.aay2645

Article Figures & Data Info & Metrics eLetters PDF

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Generating large-scale cluster states

The development of a practical quantum computer requires universality, scalability, and fault tolerance. Although much progress is being made in circuit platforms in which arrays of qubits are addressed and manipulated individually, scale-up of such systems is experimentally challenging. Asavanant *et al.* and Larsen *et al.* explore an alternative route: measurement-based quantum computation, which is a platform based on the generation of large-scale cluster states. As these are optically prepared and easier to handle (one simply performs local measurements on each individual component of the cluster state), such a platform is readily scalable and fault tolerant. The topology of the cluster state ensures that the approach meets the requirements for quantum computation.

Science, this issue p. 373, p. 369

Science
Vol 366, Issue 6463
18 October 2019

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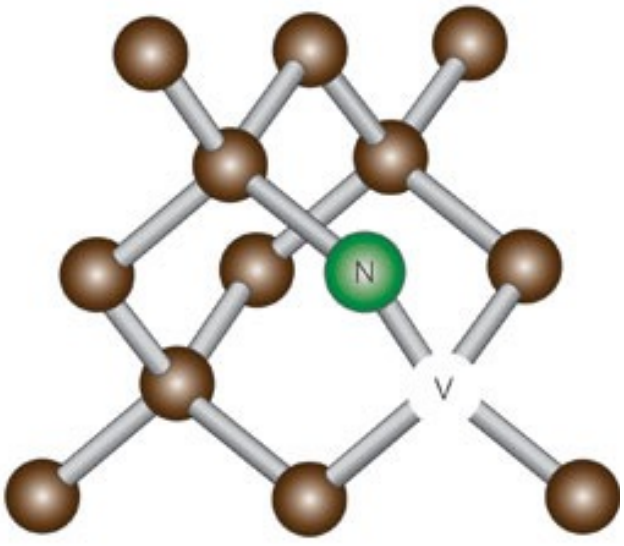
Asavanant et al, Science, 366, 6463, p373-376, 2019

NV Centres



Nitrogen Vacancy centre in diamond forms a *room temperature*, electronic spin-1 system which can be manipulated with microwave fields, and read out optically.

Image: Ahanovic et al Nature Photonics, 2011

NV Centres (2)

The Qubit: The electronic spin-1 system of an NV defect in diamond. Can be coupled to nearby nuclear spins.

Number of Qubits Demonstrated: 10

Fidelity reported: 99.2%

Pros:

- Room temperature
- Biologically compatible
- First loophole-free violation of Bell's inequalities (Delft)

Challenges:

- Coupling two NVs is difficult
- Diamond difficult to work with, scale

NV quantum memory

THE UNIVERSITY OF MELBOURNE

Featured in Physics | Open Access

A Ten-Qubit Solid-State Spin Register with Quantum Memory up to One Minute

C. E. Bradley, J. Randall, M. H. Abobeih, R. C. Berrevoets, M. J. Degen, M. A. Bakker, M. Markham, D. J. Twitchen, and T. H. Taminiau

Phys. Rev. X **9**, 031045 – Published 11 September 2019

Physics See Synopsis: Diamond Qubits Take the Stage

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ABSTRACT

Spins associated with single defects in solids provide promising qubits for quantum-information processing and quantum networks. Recent experiments have demonstrated long coherence times, high-fidelity operations, and long-range entanglement. However, control has so far been limited to a few qubits, with entangled states of three spins demonstrated. Realizing larger multiqubit registers is challenging due to the need for quantum gates that avoid cross talk and protect the coherence of the complete register. In this paper, we present novel decoherence-protected gates that combine dynamical decoupling of an electron spin with selective phase-controlled driving of nuclear spins. We use these gates to realize a ten-qubit quantum register consisting of the electron spin of a nitrogen-vacancy center and nine nuclear spins in diamond. We show that the register is fully connected by generating entanglement between all 45 possible qubit pairs and realize genuine multipartite entangled states with up to seven qubits. Finally, we investigate the register as a multiqubit memory. We demonstrate the protection of an arbitrary single-qubit state for over 75 s—the longest reported for a single solid-state qubit—and show that two-qubit entanglement can be preserved for over 10 s.

Issue

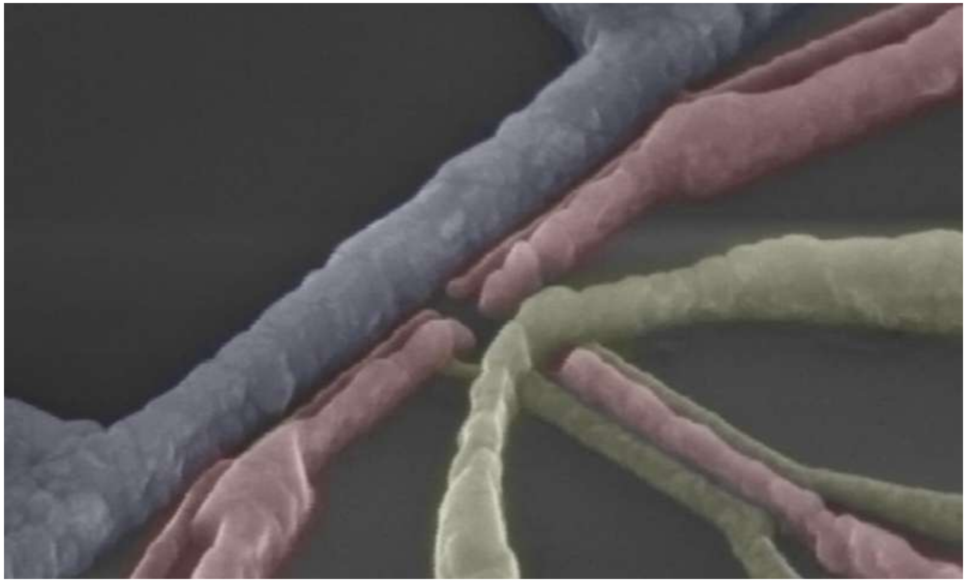
Vol. 9, Iss. 3 — July - September 2019

Subject Areas

Condensed Matter Physics
Quantum Physics
Quantum Information

Check for updates

Semiconductor Donors and Dots



UNSW. Qubits are the states of individual donors (either electron or nuclear spins) or the electronic levels of quantum dots (act as artificial atoms).

Donors and Dots (2)

The Qubit: The electrons spin or nuclear spin degrees of freedom of a donor or a dot.

Number of Qubits Demonstrated: 3+

Fidelity reported: > 99%

Pros:

- Intrinsically extremely long decoherence times (3s/minutes)
- Existing semiconductor industry at scale
- Comparatively small

Challenges:

- Need more qubits and coupling

Company support

Intel, Commonwealth Bank, Telstra

Donors: A two qubit swap gate

THE UNIVERSITY OF MELBOURNE

MENU nature
International journal of science

Letter | Published: 17 July 2019

A two-qubit gate between phosphorus donor electrons in silicon

Y. He, S. K. Gorman, D. Keith, L. Kranz, J. G. Keizer & M. Y. Simmons

Nature **571**, 371–375 (2019) | Download Citation

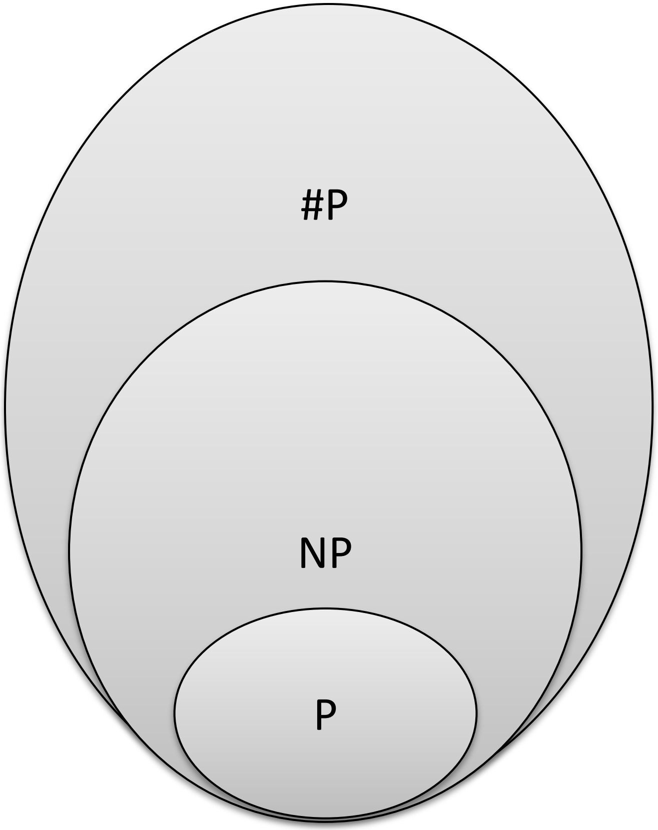
Abstract

Electron spin qubits formed by atoms in silicon have large (tens of millielectronvolts) orbital energies and weak spin–orbit coupling, giving rise to isolated electron spin ground states with coherence times of seconds[1,2]. High-fidelity (more than 99.9 per cent) coherent control of such qubits has been demonstrated[3], promising an attractive platform for quantum computing. However, inter-qubit coupling—which is essential for realizing large-scale circuits in atom-based qubits—has not yet been achieved. Exchange interactions between electron spins[4,5] promise fast (gigahertz) gate operations with two-qubit gates, as recently demonstrated in gate-

He et at, Nature, 571, 371-375 (2019)

Quantum Complexity Classes

Some classical complexity classes



P: Problems which can be solved in polynomial time

NP: Problems which can be checked in polynomial time (ie. they have an efficiently verifiable proof)

#P: Problems which count the number of solutions in NP

What are the equivalent for quantum computers?

Complexity classes with error

BPP is Bounded error Probabilistic Polynomial time. Polynomial time, but on a probabilistic computer allowing for an error of as much as 1/3.

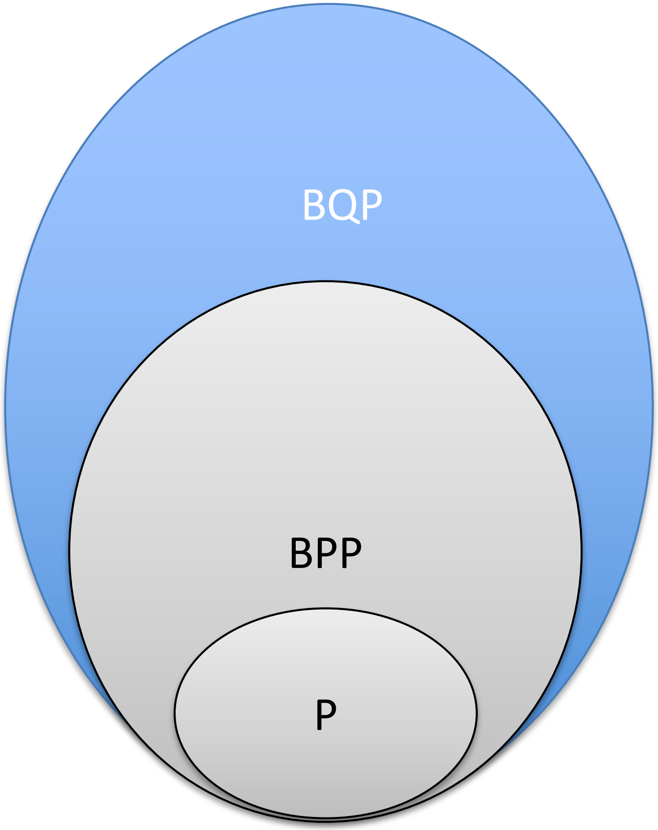
- Can flip coin and make random decisions
- Guaranteed to run in polynomial time
- On any given run of the algorithm has a probability <1/3 of the wrong answer, whether the answer is TRUE or FALSE.

BQP

Bounded error **Q**uantum **P**olynomial Time

BQP is the set of decision problems solvable by a quantum computer in polynomial time, with an error of at most 1/3.

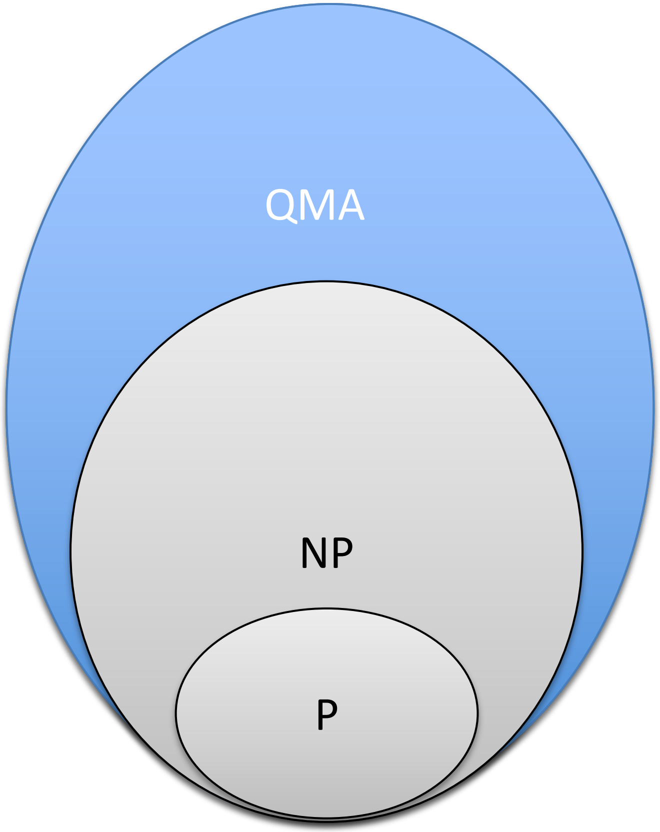
Polynomial Time Algorithms



BPP = P?

So BQP is (roughly, including error) the quantum equivalent of P/BPP. What’s the analogy to NP?

QMA and QMA Complete



Quantum **M**erlin-**A**rthur (QMA) is the analog of NP.

Informally:

NP is the set of problems you can verify in polynomial time.

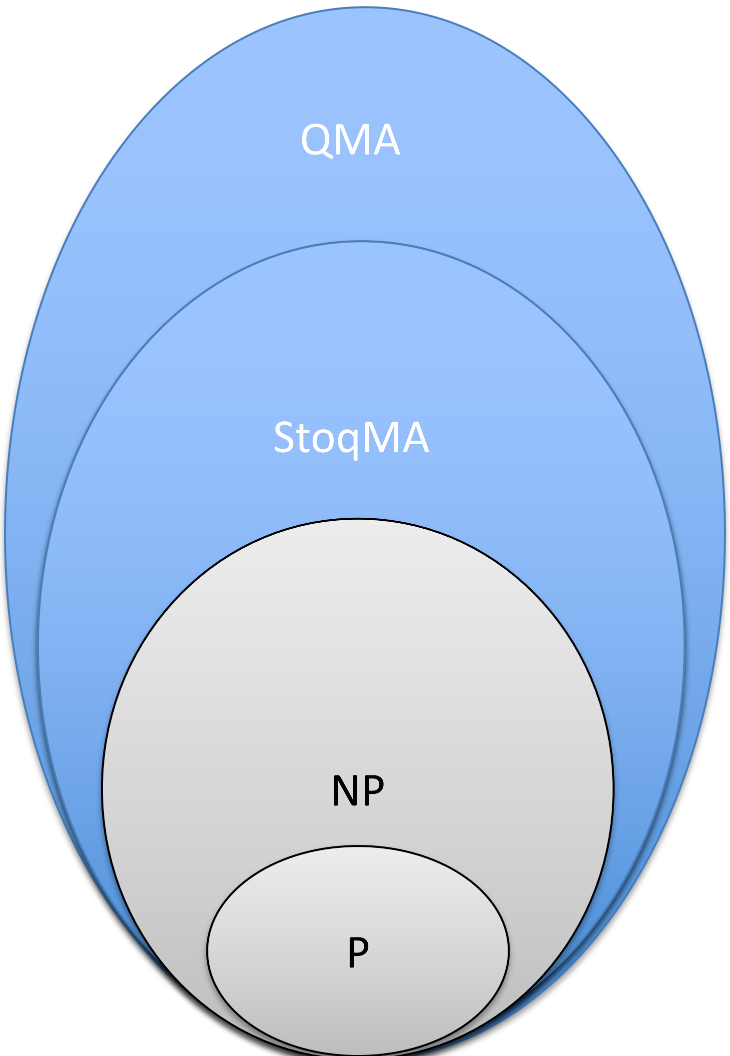
QMA is the set of problems you can verify in polynomial time with a quantum "proof".

Example: Is does the lowest energy eigenstate of local Hamiltonian H have an energy less than E_a or are all the energies greater than E_b?

Verification uses a quantum state as a "proof", and measure the energy!

QMA Complete: The hardest problems in QMA. Can map any problem in QMA onto these.

"Stoquastic" Hamiltonians



Not all Hamiltonians are equally hard to find the ground state of. In fact, those we have using for quantum annealing are easier in comparison to a general local Hamilonian. These types of Hamiltonians are known as stoquastic Hamiltonians, and have their own complexity class:

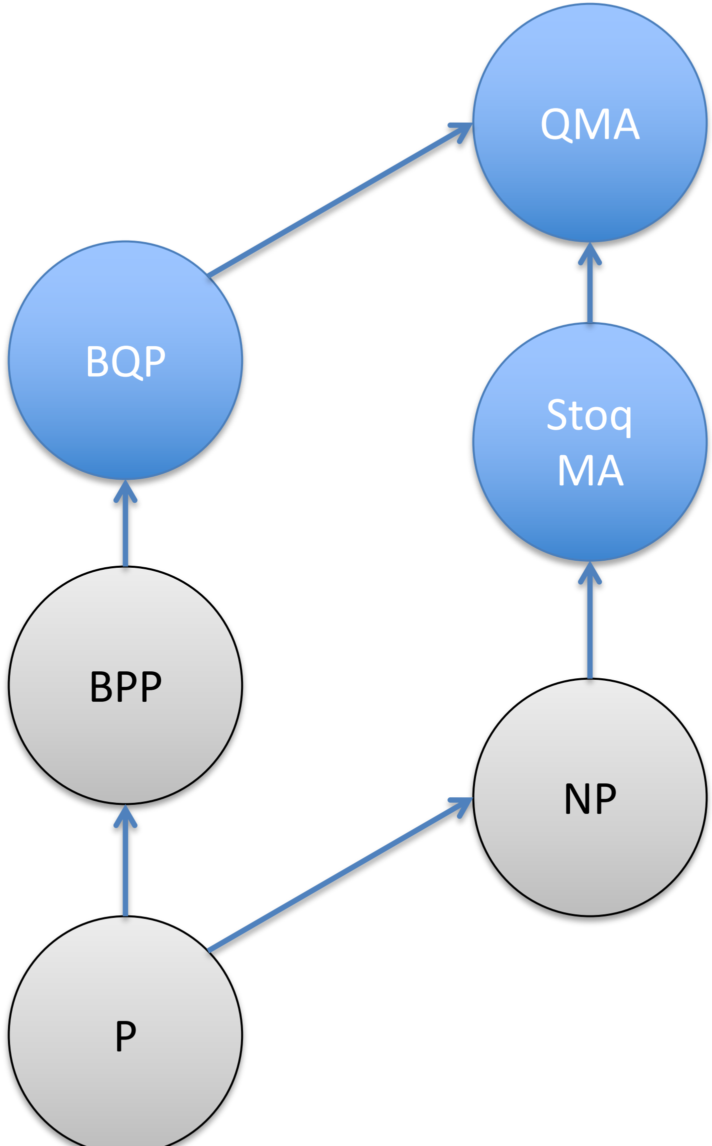
StoqMA

Technically, a **Stoquastic matrix** is a Hermitian matrix, where all off-diagonal elements are real and non-positive.

Clearly, since we've been encoding NP-complete problems like MAX-CUT StoqMA includes NP.

Fitting it all together

Quantum Complexity Classes



Classical Complexity Classes

Week 12

Lecture 23

Quantum Computing architectures and quantum complexity classes

Lecture 24

Quantum Computing Review

Lab 12

HHL algorithm using the QUI