Implementations of Quantum Computing

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Experimental QIP

- Realising quantum information processing in a lab is extremely difficult
- Requires two almost mutually-exclusive conditions:
  - Low decoherence
    - i.e., an isolated, closed system
  - Strong control
    - i.e., strongly coupled to user
- Experimental effort: to gain strong, precise control over quantum systems that maintain their quantum nature
Example 1: spin of electrons

- The spin of an electron gives a two-level system
- We have strong control over this spin using electric and magnetic fields
- But through spin-spin interactions, a single electron spin couples to every other electron nearby!
Example 2: polarised photons

- The polarisation of a photon gives a two-level system.
- Photons in free space do not interact with each other (i.e., with electric or magnetic fields).

But how can we entangle two photons if we can’t interact them?
DiVincenzo criteria

David DiVincenzo (IBM) – requirements for a quantum computer:

1. The machine must have a scalable collection of bits
   Each bit must be individually addressable, and it must be possible to scale up to a large number of bits

2. It must be possible to initiate all of the bits to zero

3. The error rate should be sufficiently low
   Decoherence times must be much longer than the gate operation times

4. It must be possible to perform elementary logical operations between pairs of bits

5. Reliable readout of the final result must be possible
Physical implementations

Many sub-fields of physics have proposals for QC

- Liquid-state NMR
- NMR spin lattices
- Linear ion-trap spectroscopy
- Neutral-atom optical lattices
- Cavity QED + atom
- Linear optics
- Nitrogen vacancies in diamond
- Electrons in liquid He
- Superconducting Josephson junctions
  - charge qubits
  - flux qubits
  - phase qubits
- Quantum Hall qubits
- Coupled quantum dots
  - spin, charge, excitons
- Spin spectroscopies, impurities in semiconductors
Ion traps

- **Qubit**: internal electronic state of atomic ion in a trap (ground and excited)
- **Coupling**: use quantised vibrational mode along linear axis (phonons)
- **Single qubit gates**: using laser

The latest:

Monroe group – UMich

“T-Junction trap”

Shuttling ions around corners

Linear optics

- Qubit: polarisation of a single photon
- Coupling: via measurement
- Single-qubit gates: polarisation rotation

$$|\psi\rangle = \psi_0|0\rangle + \psi_1|1\rangle + \psi_2|2\rangle$$

$$|\psi'\rangle = \psi_0|0\rangle + \psi_1|1\rangle - \psi_2|2\rangle$$

The latest:
Zeilinger group – UVienna
“One-way” quantum computing with four qubits

Superconducting Josephson junctions

Qubit:  
   a) Magnetic flux trapped in loop  
   b) Cooper pair charge on metal box  
   c) Charge-phase  
   - Coupling: capacitive/inductive  
   - Single-qubit gates: flux bias, charge on gate, current through junction  

The latest:  
Schoelkopf group – Yale  
Coherent coupling of a single photon to a superconducting qubit (Cooper pair box)  

Nuclear magnetic resonance (NMR)

- Qubit: nuclear spins of atoms in a designer molecule
- Coupling and single-qubit gates: RF pulses tuned to NMR frequency


Silicon quantum computing

- Qubit:
  - Nuclear spin of single P donor
  - Electron spin of single donor
- Coupling: gate-controlled electron-electron interaction
- Single-qubit gates: NMR pulse; gate bias in magnetic material

The state of play

The Mid-Level Quantum Computation Roadmap: Promise Criteria

<table>
<thead>
<tr>
<th>QC Approach</th>
<th>Quantum Computation</th>
<th>QC Networkability</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>#1</td>
<td>#2</td>
</tr>
<tr>
<td>NMR</td>
<td>🍊</td>
<td>🍊</td>
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<tr>
<td>Trapped Ion</td>
<td>🍊</td>
<td>🍊</td>
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<tr>
<td>Neutral Atom</td>
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<td>Solid State</td>
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<tr>
<td>Superconducting</td>
<td>🍊</td>
<td>🍊</td>
</tr>
<tr>
<td>Unique Qubits</td>
<td>This field is so diverse that it is not feasible to label the criteria with “Promise” symbols.</td>
<td></td>
</tr>
</tbody>
</table>

Legend:
- 🍊 = a potentially viable approach has achieved sufficient proof of principle
- 🍊 = a potentially viable approach has been proposed, but there has not been sufficient proof of principle
- 🍊 = no viable approach is known

The column numbers correspond to the following QC criteria:
#1. A scalable physical system with well-characterized qubits.
#2. The ability to initialize the state of the qubits to a simple fiducial state.
#3. Long (relative) decoherence times, much longer than the gate-operation time.
#4. A universal set of quantum gates.
#5. A qubit-specific measurement capability.
#6. The ability to interconvert stationary and flying qubits.
#7. The ability to faithfully transmit flying qubits between specified locations.

ARDA Quantum Computation Roadmap
2 April 2004
http://qist.lanl.gov
Summary

- Quantum computation requires precise control over isolated systems
- Many possible physical realisations may lead to discoveries and advances in quantum computation
- Are we at the turning point?
  - Recent theoretical results strongly suggest QC is feasible
  - Recent experimental developments suggest we might be there soon

Australia is a major player
UNSW, Melbourne and Queensland: experiment
Queensland, Sydney, Macquarie, Griffith: theory