Quantum Computing

Level 2 Physics

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Outline

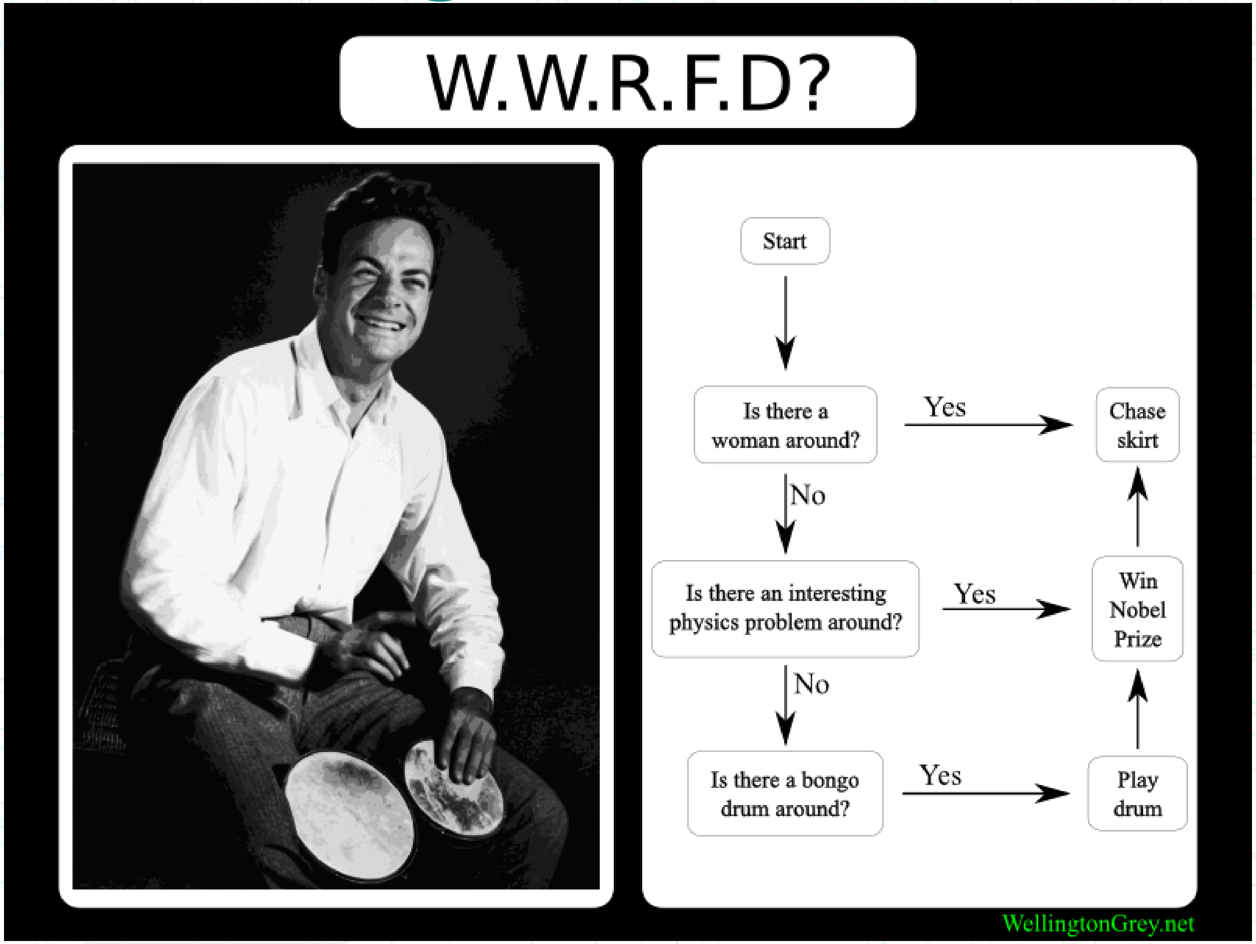
- What is Quantum Computing?
- Origins of Quantum Computing
- Quantum Information: The Qubit
- Computing with Qubits
- Implementing Quantum Computers

What Is Quantum Computing?

A quantum computer is one that harnesses the phenomena found at the quantum scale to compute, typically at speeds greater than that of conventional computers.

– J. Arnold, 2008

Origins of QC



1982: Richard Feynman
Quantum Computing Postulated

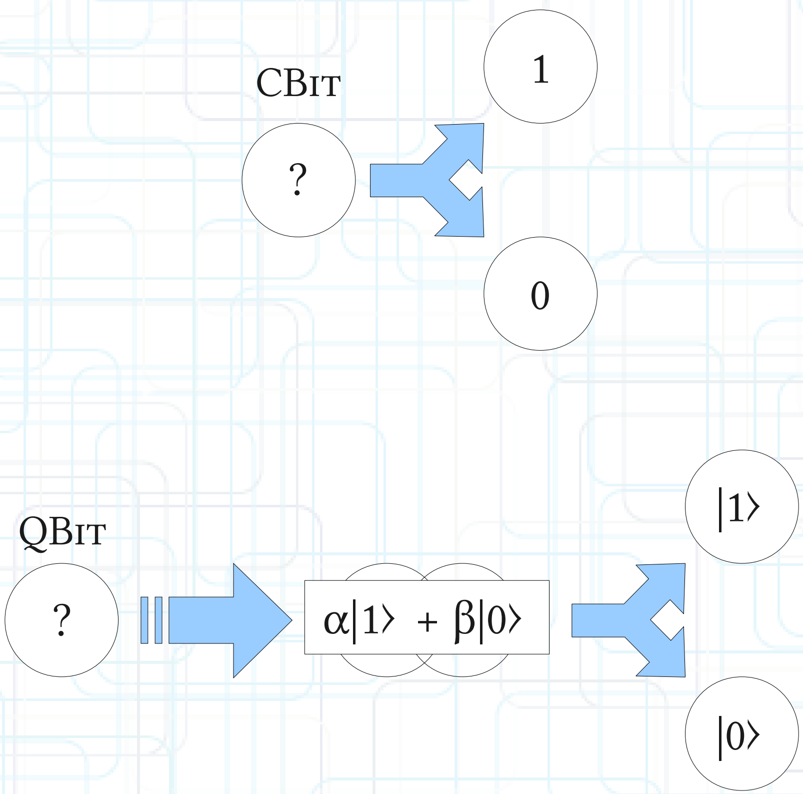
Origins of QC

1994: Peter Shor
First QC Algorithm

The Qubit

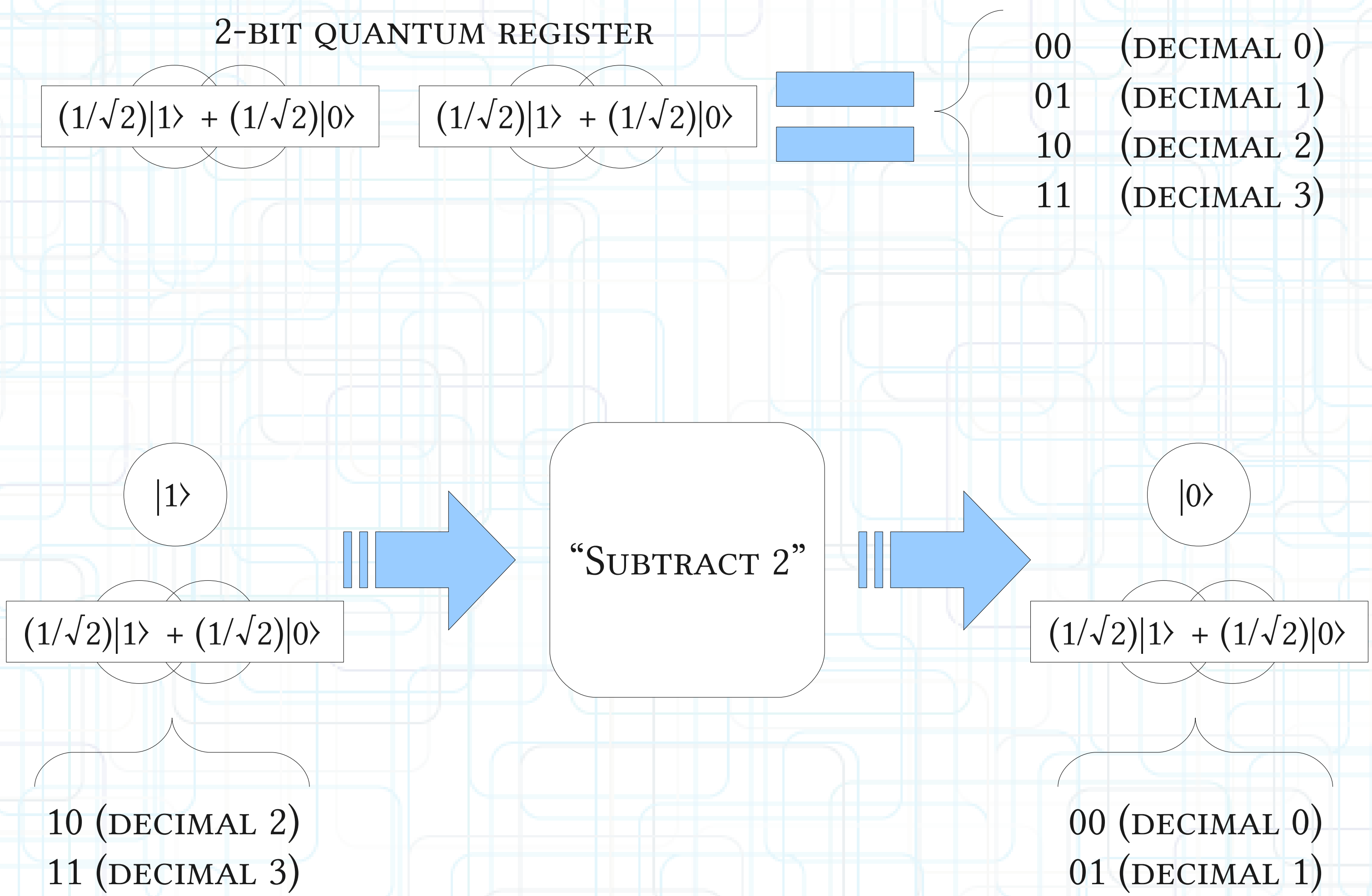
- Basic building block of quantum computing
- Analogous with classical 'bit'
- Electron, photon – anything with a two-state property, e.g.:
  - Spin
  - Polarisation
- Exhibits quantum mechanical phenomena
  - Superposition
  - Entanglement

The Qubit – Superposition



- Conventional Computer – 1 **or** 0
- Quantum computer – 1, 0, **or both**

The Qubit – Superposition



The Qubit – Entanglement

- High correlation between particles
- Irrelevant of basis
- Non-local correlation
- 'Spooky action-at-a-distance'
  – Albert Einstein

(yes, this is Einstein...)

Computing With Qubits

- Arranged in registers
- Often entangled

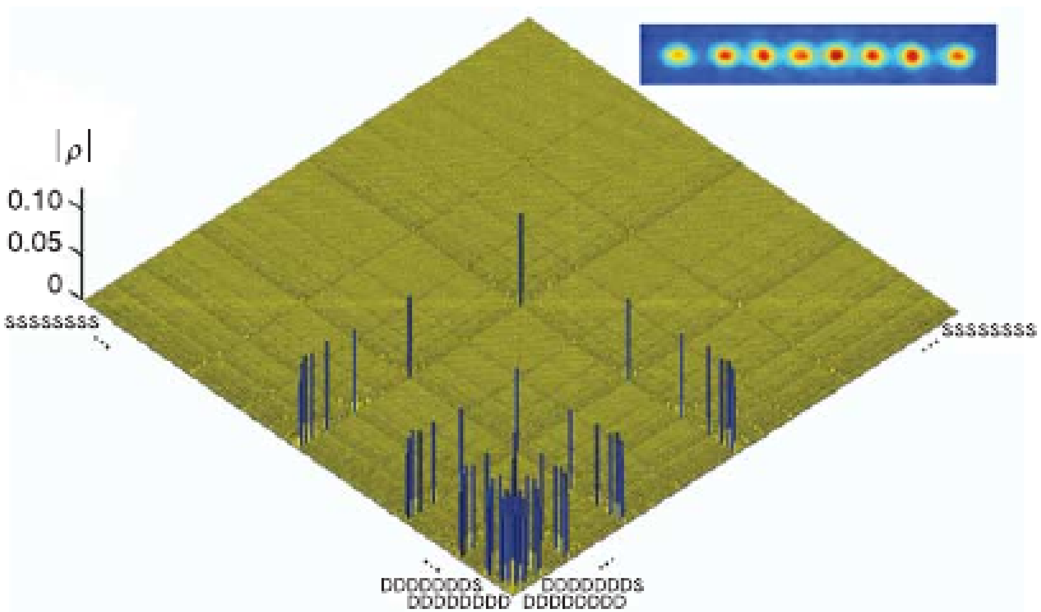


Figure 1 | Absolute values, $|\rho|$, of the reconstructed density matrix of a $|W_8\rangle$ state as obtained from quantum state tomography. DDDDDDDD…SSSSSSSS label the entries of the density matrix ρ. Ideally, the blue coloured entries all have the same height of 0.125; the yellow coloured bars indicate noise. Numerical values of the density matrices for $4 \leq N \leq 8$ can be found in Supplementary Information. In the upper right corner a string of eight trapped ions is shown.

– H. Haffner et al, *Scalable Multiparticle Entanglement of Trapped Ions*, Nature, **438**, p. 643-646 (2005)

Gates

- Basic logical operators
- *Universal Set* gives gates that can perform every possible logical operation
- 2-bit conventional universal sets:
  - NAND
  - XOR

$$\text{NOT}\, P \equiv P\, \text{NAND}\, P$$
$$P\, \text{AND}\, Q \equiv (P\, \text{NAND}\, Q)\, \text{NAND}\, (P\, \text{NAND}\, Q)$$
$$P\, \text{OR}\, Q \equiv (P\, \text{NAND}\, P)\, \text{NAND}\, (Q\, \text{NAND}\, Q)$$
$$P\, \text{implies}\, Q \equiv P\, \text{NAND}\, (Q\, \text{NAND}\, Q)$$

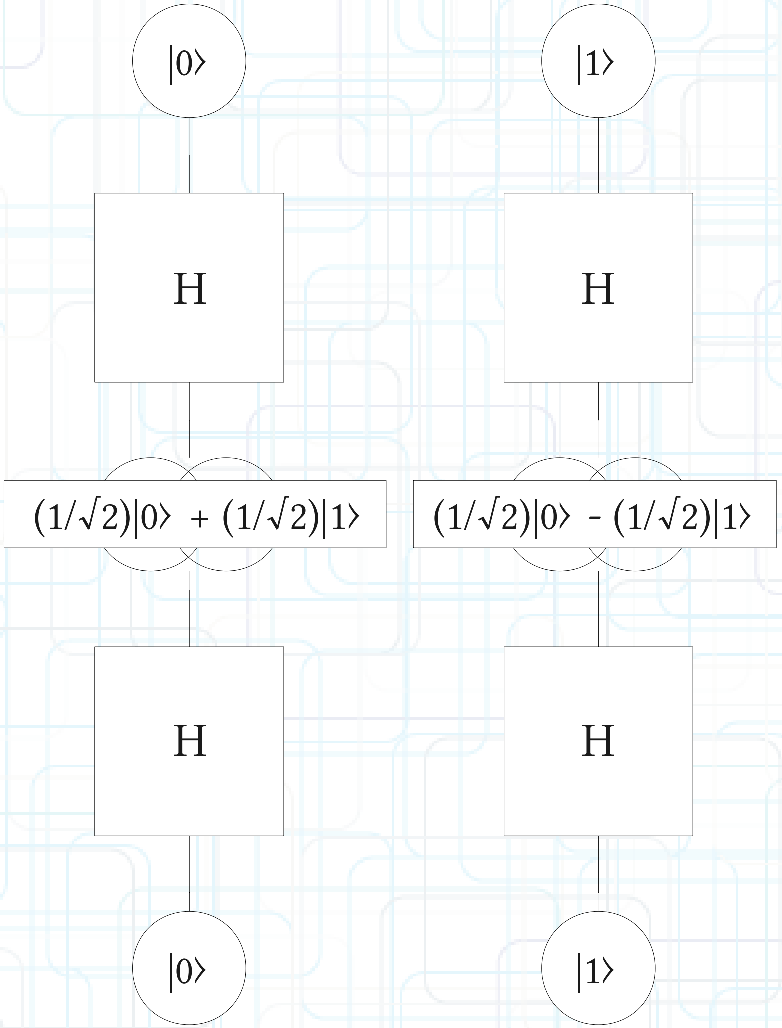
Quantum Gates

- Quantum gates cannot destroy information
- Must be reversible
- Conventional gates aren't useful:
  - Some destroy information
  - None allow superposition!
- New set of gates is required, in order to create the *universal quantum computer*

A Quantum 2-Bit Universal Set

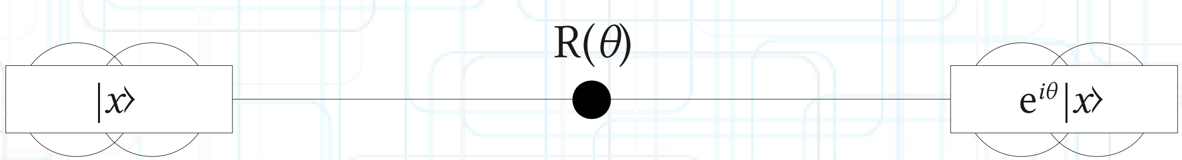
- **Hadamard Gate**
- Takes a single state and converts it into a superposition of states, and vice versa
- Operator transform matrix:

$$H = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & 1 \\ 1 & -1 \end{pmatrix}$$



A Quantum 2-Bit Universal Set

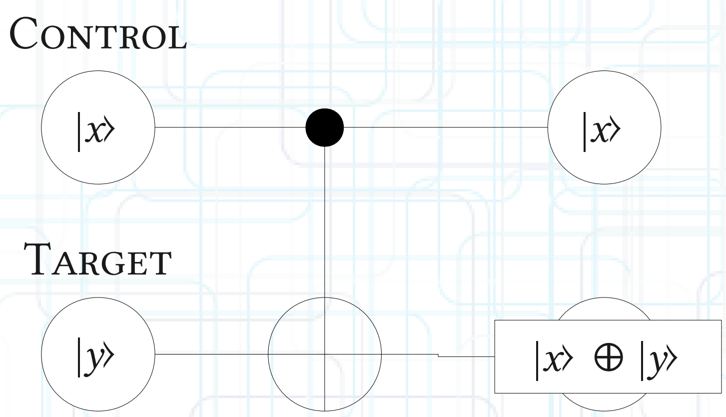
- **Phase Rotation Gate**
- Shifts $|1\rangle$-state phase of a single qubit by θ.
- Operator transform matrix: $$R(\theta) = \begin{pmatrix} 1 & 0 \\ 0 & e^{i\theta} \end{pmatrix}$$
- Universal set uses $R\left(\arccos\frac{3}{5}\right)$.



A Quantum 2-Bit Universal Set

- **Controlled NOT Gate (CNOT Gate)**
- Flips target bit if control bit is 1.
- Operator transform matrix:

$$\mathrm{CNOT} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{pmatrix}$$



Before		**After**	
Control	*Target*	*Control*	*Target*
0	0	0	0
1	0	1	1
0	1	0	1
1	1	1	0

Implementing Quantum Computers – Problems

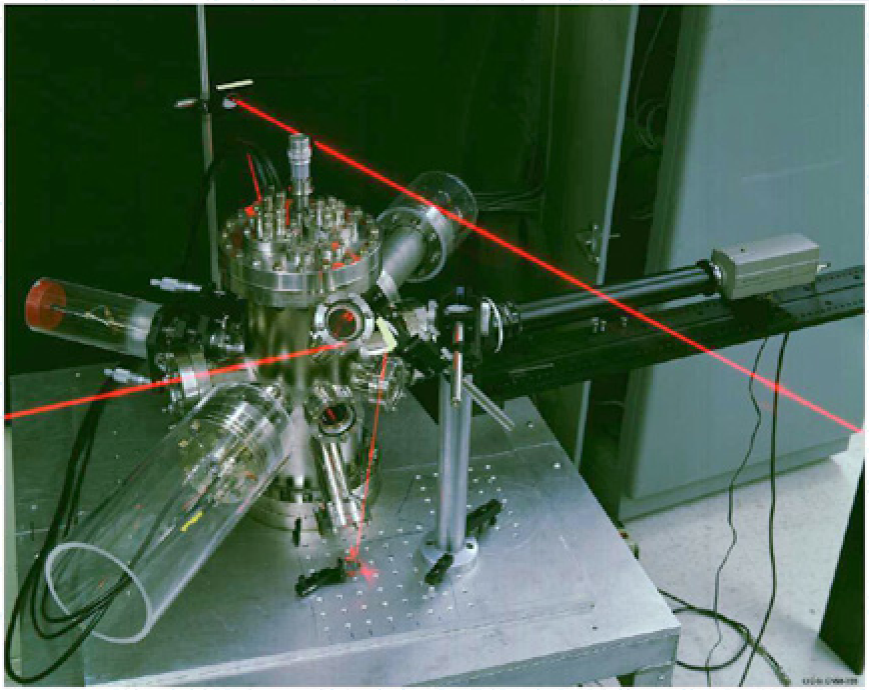
- Decoherence
- Quantum Error Correction
  - Corrects *without* measuring!
  - The Shor Code (9 physical qubits per logical qubit)
- Quantum computing will not be faster for all problems – algorithms must be designed to take advantage of quantum phenomena
  - Factoring integers – Shor's Algorithm
  - Quantum Fourier Transforms
  - Searching – Grover's Algorithm

Implementing Quantum Computers – Methods

- No particular method is the standard yet – still in research
- Many different implementations:
  - Trapped Ion
  - Optical Lattice
  - NMR
- Trapped Ion currently the most promising, due to high entanglement fidelity and long decoherence time

Implementations of Quantum Computers

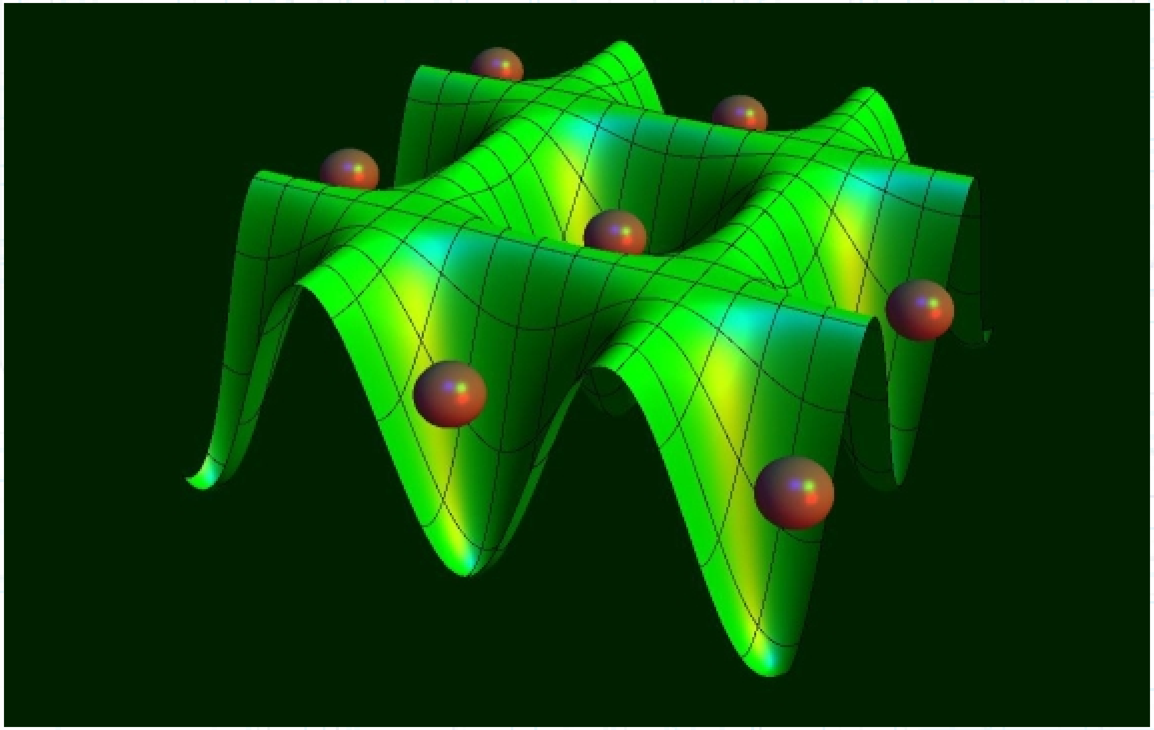
- **Ion Trapping**
- Qubits are the electron configuration of ions
- Kept in place by electromagnetic fields



– Vacuum Chamber for preparing ions, Los Alamos, 2008

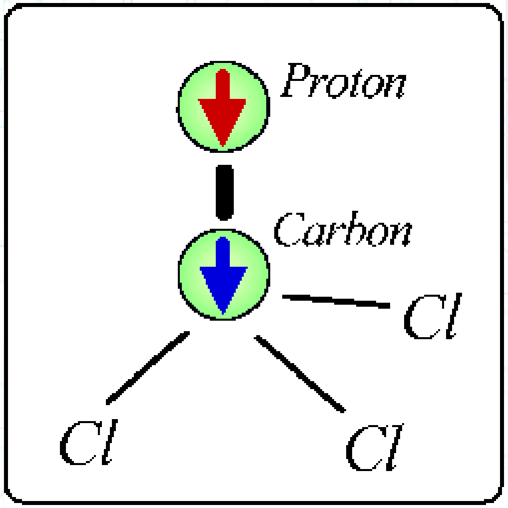
Implementations of Quantum Computers

- **Optical Lattice**
- Qubits are the electron configuration of ions
- Kept in place by interfering lasers, creating wells of potential for the ions to sit in



Implementations of Quantum Computers

- **NMR Quantum Computing**
- Qubits stored as spin of certain atoms in a molecule (here, chloroform)
- Held in place and altered using static magnetic fields and radio pulses.



$$|0\rangle|0\rangle$$

Summary

- Quantum computers make use of quantum mechanical phenomena to reduce computing times for certain problems
- Quantum computing has not been around for very long, and is still in the research phase
- A universal quantum computer has been theorised, but not implemented
- Decoherence needs to be reduced, multiparticle entanglement needs to be improved and algorithms (error correction and calculation) need to be devised to progress the field