CSCI 4140
Trapped Ion Quantum Computers

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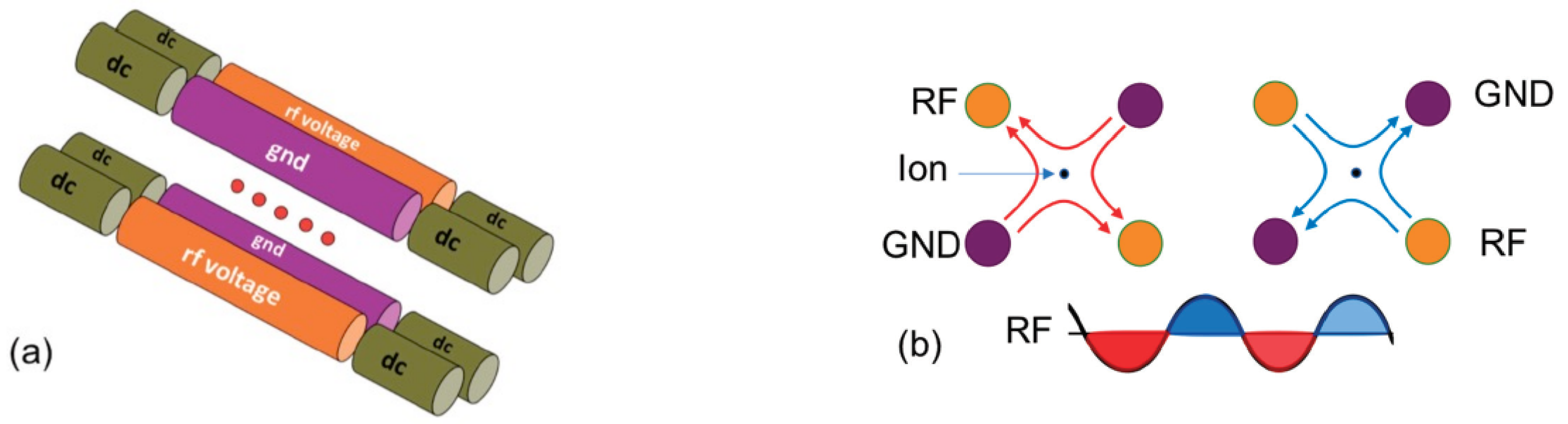
Introduction

- One of the main technologies and fairly easy to understand
- One of the more mature technologies
- Provides long coherence time, on the order to seconds
- Error rates in the 10^{-4} range
- Must operate in a vacuum, but don’t need super cooling
- Gate times are relatively slow
- Challenge: scaling to large number of qubits

Basic Idea

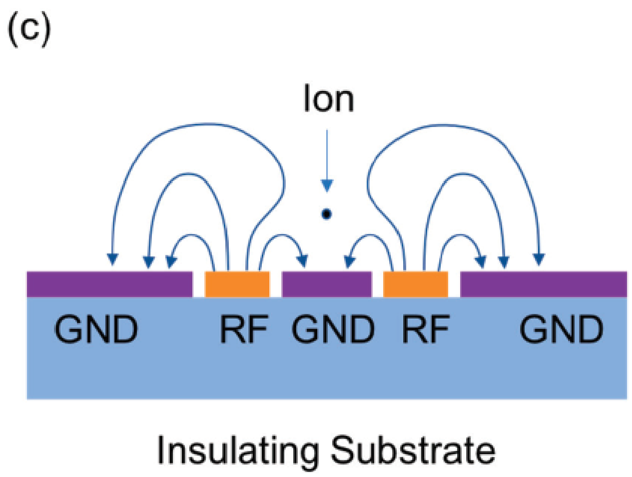
- Trapped ion quantum computers have been investigated for many decades -> many different techniques have been developed
- Too many variations to completely cover here, will concentrate on one approach to demonstrate the basic ideas
- Examine to Honeywell implementation, state of the art
- The starting point is an ion, an atom with a positive charge
- Since it has a charge a single ion can be suspended in space using a electrical field, called a Paul trap

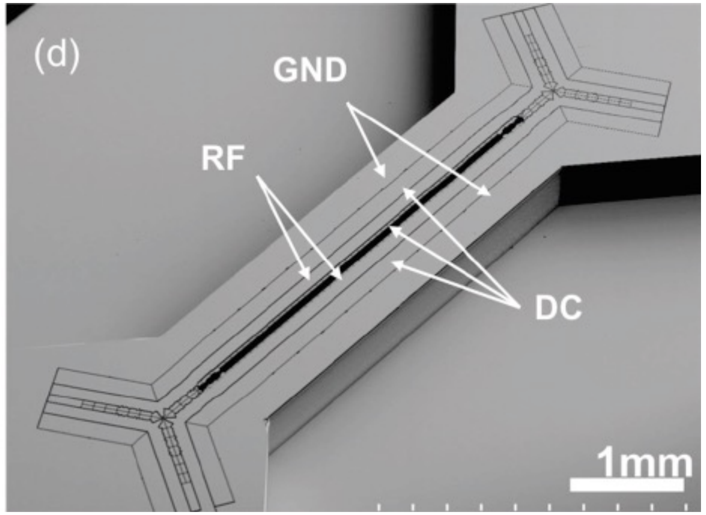
Paul Trap



An RF field is used to stabilize the ion, otherwise the ion
Tends to spin and move in space

Paul Trap





The trap can be folded flat so it can be fabricated using using standard IC fabrication techniques

Ions

- Both the electrical energy and motion states are used in the quantum computations
- To states are selected for |0> and |1>, usually |0> is one of the stable ground states of the atom
- The |1> state can have higher or lower energy, but typically isn’t as stable
- For optical ion traps the states are widely separated, the energy difference corresponds to the visible light region
- Lasers used to manipulate the ions

Ions

- The vibrational motion states are used to encode entanglement, this can be done over multiple qubits
- The simplest arrangement of ions is in a straight line, each ion is separated by a small distance, and the complete trap is in a vacuum
- 2D arrangements of ions is also possible, this gives more flexibility in organizing the ions
- Note: ions can be moved by applying an electrical force to them

Aside - Large Ion Traps

- The largest research ion trap is currently 300 ions arranged in a 2D grid
- Challenges are getting them placed correctly and controlling them
- Have shown that you can effectively use 160 of them as qubits in computations
- Don’t use the gate model of quantum computing, work at a lower level

Ions

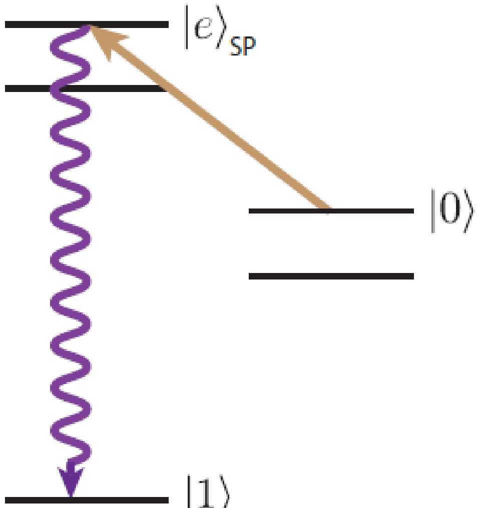
- Ions must be generated and then injected into the ion trap, called loading
- There are several techniques for this, they typically take several seconds or longer
- Once the trap has been loaded the ions can stay in it for hours or even days, so this isn't a frequent operation
- To start a computation the ions are "cooled" to their $|0\rangle$ state
- Since there is a small number of ions in a vacuum, temperature doesn't make a lot of sense

Ions

- Ions are cooled using a laser, the idea is to excite the atom to an unstable high energy state which will quickly transition to the $|0\rangle$ state
- Once all the ions are in the $|0\rangle$ state, some will need to be changed to the $|1\rangle$ state as their initial value
- This is done using a laser to excite the $|0\rangle$ state to an unstable higher energy state that quickly decays to the $|1\rangle$ state
- The laser wavelength corresponds to the energy difference between the states

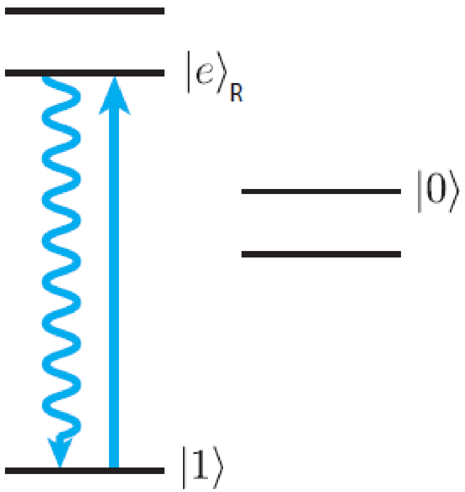
Ions

(a)



State preparation

(c)



State detection

Ions

- Measuring qubits again uses a laser for state transition
- Select a laser wavelength that causes the |1> state to transition to a higher energy state that quickly decays emitting a photon
- The wavelength has no impact on the |0> state, there is no state it can transition to with that energy level
- Then measure the photons that are produced
- This process needs to be repeated several times (~7) to generate enough photons

Gates

- Gates are fairly complicated, won’t go into the details
- Again lasers are used to manipulate the qubits
- Single qubit gates with rotations are fairly easy to do, speeds are in the 600-800 nsec range, about 100x slower than digital
- Two qubit gates are in the μsec range, error rates are in the 10^{-4} range
- Multiple gates can be applied at the same time if there is physical distance between the qubits

Video

- https://www.youtube.com/watch?v=aV1wL5jsfRU

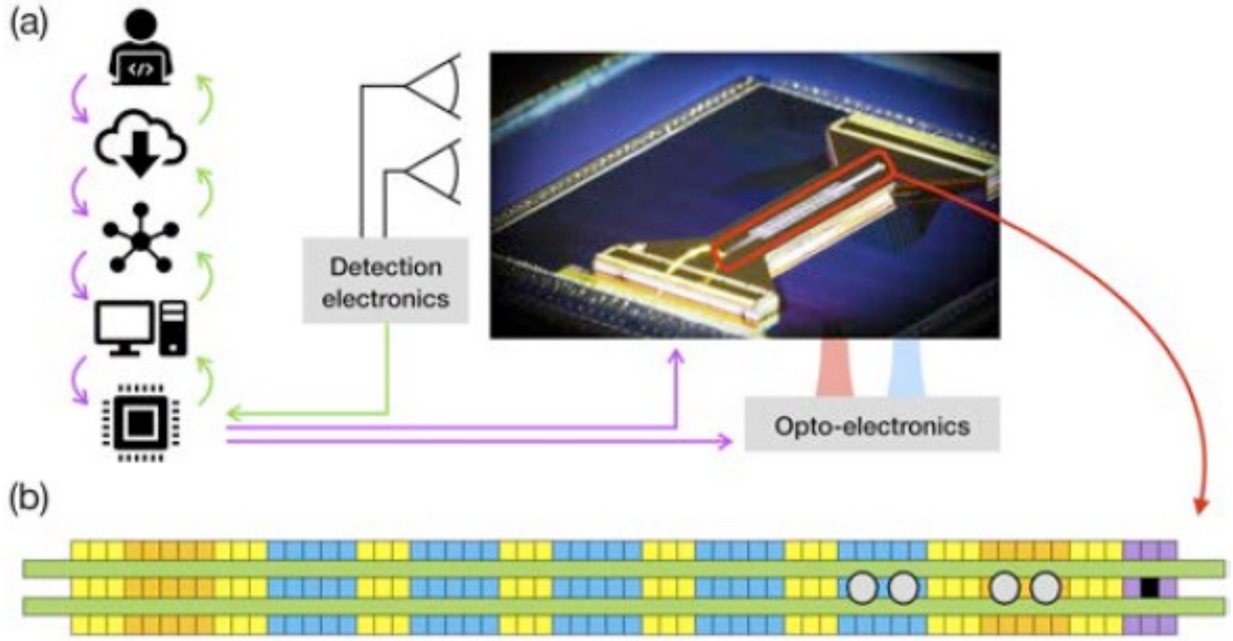
Honeywell Example

- State of the art in ion trap quantum computers
- A demonstration system, used to measure the quality of their approach
- The demonstration and research version uses 4 qubits, the commercial version has 6 qubits
- The plan is to physically connect multiple ion traps so ions can move between the traps
- A modular approach to building a quantum computer

Honeywell Example

- Based on a linear trap that is divided into a number of zones
- Ions can be moved between zones using DC fields
- They envision accessing this through the cloud, users produce programs that are compiled into an FPGA that is used to control the trap
- The program is run, the results are measured and sent back to the user through the cloud
- This is illustrated on the left side of the next slide

Honeywell Example



Honeywell Example

- The bottom part of the figure is a schematic of the trap
- At the right end is the ion source, the black dot is the point where the ions enter the trap
- The blue zones are where gates can be applied to the qubits
- The two orange zones are used for qubit storage, along with the yellow zones between the gate zones
- The qubits can be moved between the zones and any pair of qubits can be rotated to swap them

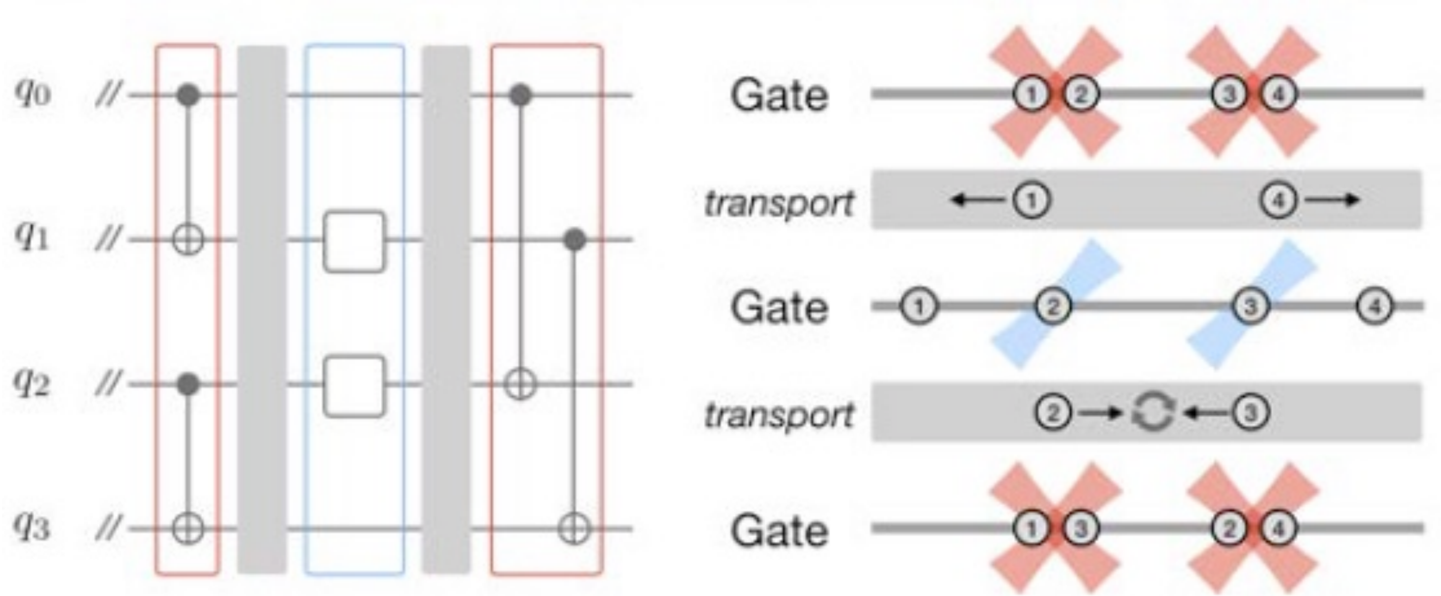
Honeywell Example

- Each qubit is represented by two ions:
  - The $^{171}Yb^{+}$ is used to represent the qubit state
  - The $^{138}Ba^{+}$ is used to assist with cooling the qubit
- The trap is run in a vacuum that is cooled to 12.5K
- The system can perform:
  - High resolution Z rotation
  - Restricted X/Y rotation
  - Two qubit gate
  - Split and join operations on pairs of qubits

Honeywell Example

- The next slide shows an example of how the device works
- The left side is the quantum circuit, the right side is the sequence of operations in the trap
- Two pairs of qubits are brought together in a gate area and the CNOT is applied
- They are split, and a one qubit gate is applied to two of them
- They are then swapped
- Finally two more CNOTs are performed

Honeywell Example



Honeywell Example

- The gate areas are positioned 750μm apart and essentially no crosstalk between the areas have been measured
- Error measurements have been performed, they errors are in the 10^{-3} to 10^{-4} range
- They don’t report running any of the standard quantum algorithms on their system, but they have been demonstrated on other ion trap system

Interconnections

- One of the main benefits of ion traps is the ability to connect them and preserve the entangled state
- Photons are used for the connection, they can represent qubits
- The state of an ion qubit is transferred to a photon, the photon us sent to the other trap, where the state is then transferred to another ion
- Recent advances have used a different ion specifically for communications, this has improved the reliability and bandwidth

Summary

- Ion traps are the only commercially available universal quantum computers
- Honeywell is currently delivering product, IonQ may be delivering product
- There are ion trap quantum computers in the cloud
- The easiest technology to understand, also the easiest to scale
- Last year the Honeywell ion trap had the largest quantum volume of any quantum computer