QUANTUM COMPUTING: New beads on the abacus
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Classical Physics / Quantum Physics

Classical Physics
- Everyday experience
- Big objects we can look at
- Everything is smooth, continuous and sharp
- The scale of humans

Quantum Physics
- Only in the last 100 years
- Objects as small as molecules, atoms and below
- Everything is indivisibly packaged
- Things are blurry, move in jumps

Classical computing: Moore’s Law

The remarkable development of computers

- Gordon Moore:
  - in 1965 was Director of Fairchild Semiconductor
  - made a 32 transistor integrated circuit one year
  - 64 the next
- “The number of transistors (and hence computer power) doubles every 18 months to two years”
- (now making one transistor per ant per year - $10^{17}$ ants on Earth)

Motorola Power PC 620 Chip
7 million transistors
(ancient relic)

The end of Moore’s law

Prospects for the future

- Cannot get indefinite speed increases by indefinite miniaturisation
- Can get some advantages from parallel processors (more than one computer chip working together)
- BUT: Some problems will always be difficult for classical computers
- One class of these problems involves the factoring of large numbers into prime factors
**Factorizing Large Numbers**

- Essential for security of transactions over the internet ("RSA security"), etc.
- Example:
  - $127 \times 129 = 16297$ Easy! A few minutes
  - $7 \times 29083$ Hard! Maybe an hour
- "hardness" of factorizing large numbers is the key to internet security
- Best supercomputers today can manage a 140 digit number
- What about a 500 digit number? - Forget it!

REMEMBER: Fundamentally, we do not live in a classical world!

**The Quantum Computer**

- What can a quantum computer do?
  - Quantum computers do the factorization problem $10^8$ times faster than conventional computers
  - Searching through long lists
  - Quantum encryption for secure information exchange
  - Solving chemical and biological structures
  - Modelling the real (quantum) world
  - How is this done?

**The Classical World**

Use quantum particles as the bits in a quantum computer!

- Conventional computer memory states:
  - A classical computer memory can only occupy one state at a time

- Quantum computer memory states:
  - A quantum computer memory can occupy all possible states at the one time
  - The solution to the problem appears in the final state of the computer when the state of the qubits are read out
  - What can we use as qubits?

- What can we use as qubits?
  - Binary bits
  - Binary qubits

**Essential Quantum Mechanics**

We need to get a feel for these non-classical attributes:

- The art of being in two places at the one time
- Occupying two states simultaneously
- Entanglement
- "Spooky action at a distance"*

* A. Einstein
Blocking one hole gives the classical result.
"Wavefunction collapse"

First Result
- Can probe for holes in a screen with a large number of classical particles (one particle for each point on the barrier)
- Can probe for holes in a barrier with one quantum particle
- The "wave function" collapses to a particle when measured
- Quantum objects can do many things at once
- But there is more: Entanglement
Entanglement

Alice

Bob

Forward

Backwards

Entangled particles

(Spooky action at a distance)
Second Result

- Quantum objects can exist in two superimposed (entangled) states
- This superimposed state can collapse into a definite state upon measurement
- Entangled particles can be created that retain the superimposed state until measurement
- But how do we use this for quantum computing?
- We can use spin...

Spin

Sub-atomic particles spin. Look at the proton:
- A spinning charged particle acts like a tiny loop of electric current
- This produces a magnetic field
- So the spinning particle is like a tiny bar magnet

Spin and Magnetism

Spinning charged particles can be lined up with an external magnetic field

Alignment force vectors

Spin and Magnetism

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Spin and Magnetism

Space Quantisation
- Like many other properties, space itself is quantised
- The spinning particles cannot have arbitrary orientations in space relative to the external magnetic field
- The allowed orientations depend on the amount of spin
- For protons and electrons, there are only two allowed orientations
- (This is a spin-half particle)
Spin and Magnetism

Spinning subatomic particles are quantum particles
- The spin orientation are two different quantum states
- Before measurement, the spin orientation can be in two (spin 1/2) directions at the same time - superimposed states
- Upon measurement, the spin is found to point in a definite direction - wavefunction collapse
- Just what we need for a quantum computer!
- To program this computer, we need energy

Magnetic Resonance

Orientation and energy
- The spin down state is not at equilibrium
- The magnetic field twists the spin vector into alignment
- (Precise alignment is prevented by space quantisation)

Change orientations
- The high energy state will spontaneously relax back to the low energy state, releasing energy
- The low energy state can absorb energy and flip to the high energy state

A radio frequency quantum of radiation does this for protons in typical magnetic fields is 42.58 MHz/Tesla
• Excited mercury vapour emits light owing to electrons jumping up and down between energy levels
• A magnetic field placed around the vapour splits the energy levels and causes small changes in the colour of the light
• These changes can be detected with a sensitive spectrometer
• Can also see the effect in sunspots...

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Magnetic Resonance

Assign qubits

Spin up: \(|\uparrow\rangle\)
Spin down: \(|\downarrow\rangle\)

Classical equivalents

\(|\uparrow\rangle\) and \(|\downarrow\rangle\) (No classical equivalent! 1 and 0 simultaneously?)

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The Kane Quantum Computer

We are now ready to commence construction:

• "A Silicon-based nuclear spin quantum computer" by B. E. Kane, *Nature*, May 14, 1998
• Proposes a device that:
  - encodes qubits as the orientation of spinning nuclei
  - provides entanglement by means of electron clouds
  - is constructed in silicon like conventional computers
• Will use a block of pure $^{28}\text{Si}$ (spin-zero nucleus)
• Will use atoms of phosphorous ($^{31}\text{P}$) to carry the spins

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The Kane Quantum Computer

Close-up of a phosphorous atom (not to scale)
Apply radio frequency pulse

Apply radio frequency pulse

Apply radio frequency pulse

Apply radio frequency pulse

exchange coupling" mediated by J-Gates entangles spins

$J$-Gates entangles spins

$\approx 200 \text{ Å}$
Fabrication Pathways

Who is going to make this?
We are:
- Semiconductor National Nanofabrication (SNF) Laboratory, School of Physics, University of New South Wales
- Microanalytical Research Centre, School of Physics, University of Melbourne
- Laser Physics Centre, Department of Physics, University of Queensland
- Los Alamos National Laboratories, U.S.A.

Fabrication strategies:
- (1) Nano-scale lithography:
- (2) Direct $^{31}$P ion implantation

(1) Nano-scale Lithography

Step 1: Clean, flat silicon surface
Step 2: Deposit single $^{31}$P atoms
Step 3: Overgrowth by more silicon
Step 4: Deposit oxide layer
Step 5: Deposit metal contacts

20 nm

Sub-300Å AuPd gates on GaAs

(1) Nano-scale Lithography

• Electron beam lithography at the University of New South Wales

25K - 1500K Variable T
3-Chamber UHV
Plus: Si-MBE, RHEED, LEED, Auger

1nm

Image of individual atoms on silicon surface

(1) Nano-scale Lithography

• Scanning Tunneling Microscope with silicon crystal growth capabilities at the UNSW

(2) Alternative Fabrication Pathway

Difficulties:
- Must place $^{31}$P to a precision of a few billionths of a metre
- Having done that, need to come back and add metal electrodes on the buried $^{31}$P atoms for the gates
- The $^{31}$P must not move about while doing this

An alternative strategy:
- Direct $^{31}$P ion implantation
- Can create templates for electrodes automatically

(2) Direct $^{31}$P ion implantation

• Single MeV heavy ions are used to produce latent damage in plastic
• Etching in NaOH develops this damage to produce pits
• Light ions produce smaller pits

1. Irradiate
2. Latent damage
3. Etch

Ion tracks in space

- Cosmic rays struck this Apollo 8 helmet made from CR-39 plastic
- Etching in NaOH revealed the tracks

(2) Direct $^{31}$P ion implantation

- Mask $^{31}$P implant
- Etch latent damage & metallise
- Read-out state of "qubits"

Key Technologies; Imaging a single interstitial P atom

Is the human brain a quantum computer?

- Roger Penrose thinks so!

Conclusion: Quantum Computer

- Superposition and entanglement enables massive parallel processing
- Binary qubits
- (L qubits can store $2^L$ numbers at once, classical only 1)
- Shor’s prime factorization algorithm (1994) relevant to cryptography
- Grover’s exhaustive search algorithm (1996)

Quantum Computers

All Problems

Not the next step, a whole new journey*

*Prof Gerard Milburn, University of Queensland, one of our collaborators on the quantum computer project.
Further Reading

- Australian Centre for Quantum Computer Technology
- Oxford quantum computer group http://www.qubit.org
- Quantum Technology G. Milburn, Allen & Unwin, 1996
- The Large, the Small and the Human Mind, R. Penrose, Cambridge, 1997
- Quantum Teleportation, A. Zeilinger, Scientific American, April 2000
- Physics and the Information Revolution, J. Bimbaum, R.S. Williams, Physics Today, January 2000