Monash Symposium 2001
Continental Hotel, Phillip Island

QUANTUM COMPUTING: New beads on the abacus

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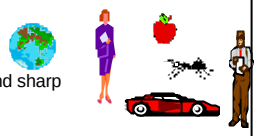
Classical Physics / Quantum Physics

Classical Physics

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



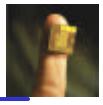
Quantum Physics

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

Classical computing: Moore's Law

The remarkable development of computers

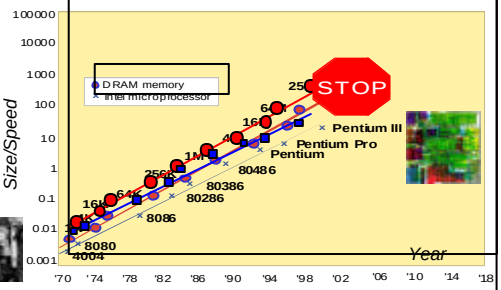
- Gordon Moore:
  - in 1965 was Director of *Fairchild Semiconductor*
  - made a 32 transistor integrated circuit one year
  - 64 the next
- "The number of transistors (and hence computer power) doubles every 18 months to two years"
- (Now making one transistor per ant per year - 10^{17} ants on Earth)



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

Ancient relics

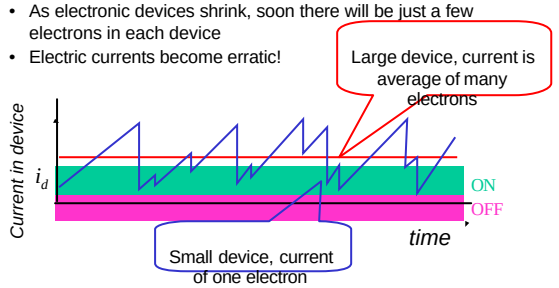
The end of Moore's law



(Turn on sound)

The end of Moore's Law!

- As electronic devices shrink, soon there will be just a few electrons in each device
- Electric currents become erratic!



Coil in LN2

Classical Computers

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 x 129 = ? Easy! A few minutes
  - ? X ? = 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!
Enter the Quantum Computer

The Quantum Computer

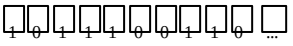
What can a quantum computer do?

- 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 Quantum Computer

Use quantum particles as the bits in a quantum computer!

- Conventional computer memory states:



binary bits

- Quantum computer memory states:

binary ***qubits***

  - 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?

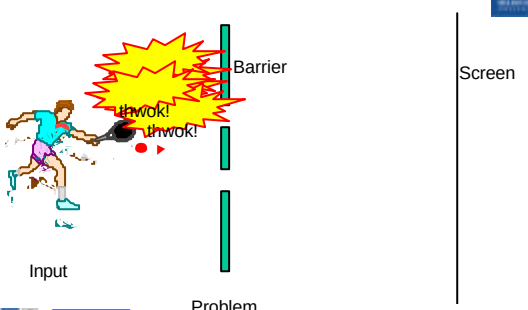
Essential Quantum Mechanics

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

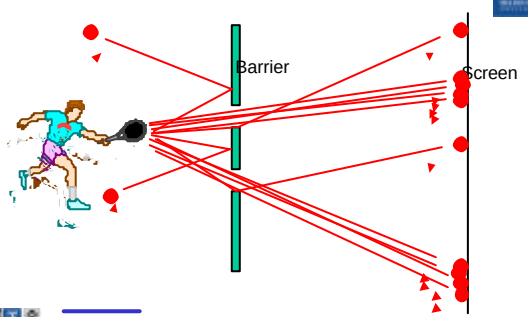
- The art of being in two places at the one time
- Occupying two states simultaneously
- Entanglement
- "Spooky action at a distance"*

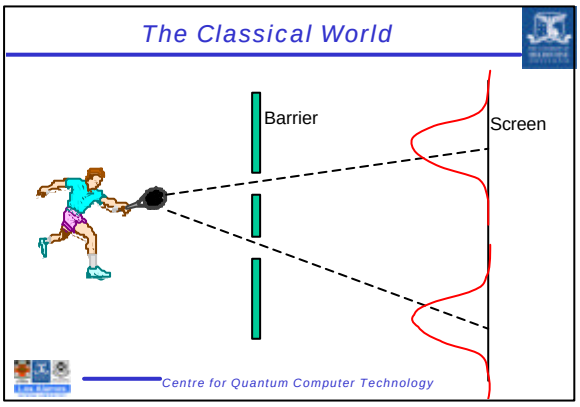
*A. Einstein

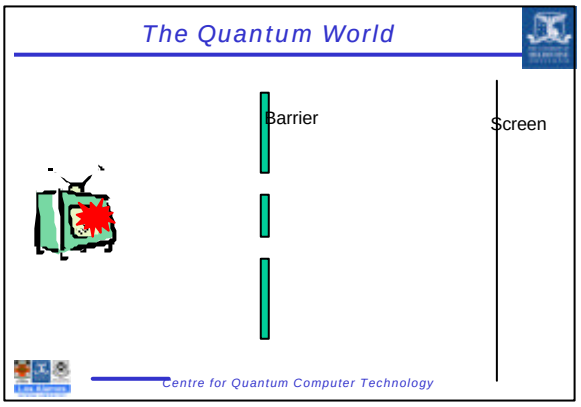
The Classical World

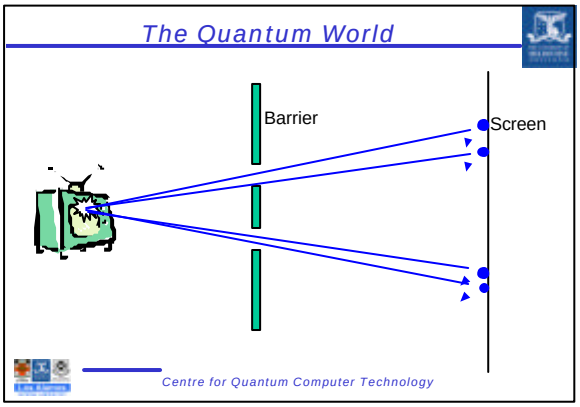


The Classical World




The Classical World
Barrier
Screen
Centre for Quantum Computer Technology


The Quantum World
Barrier
Screen
Centre for Quantum Computer Technology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Barrier
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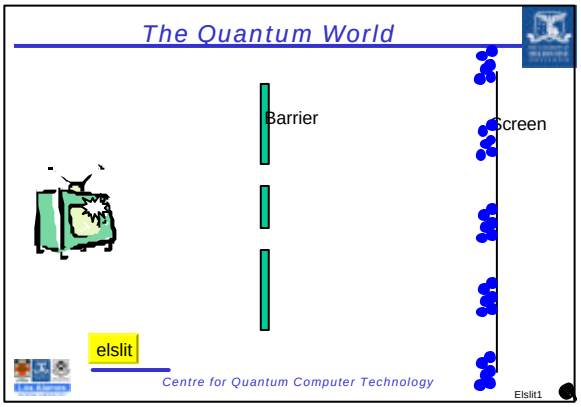
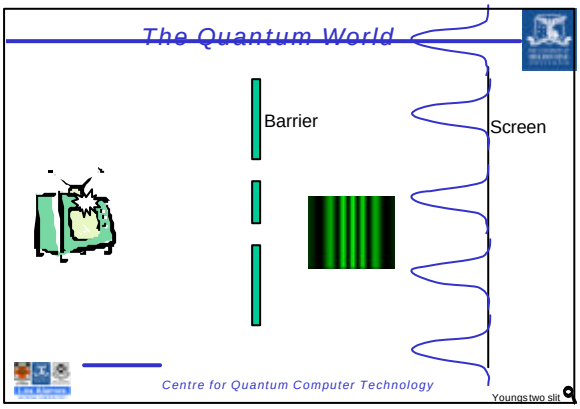
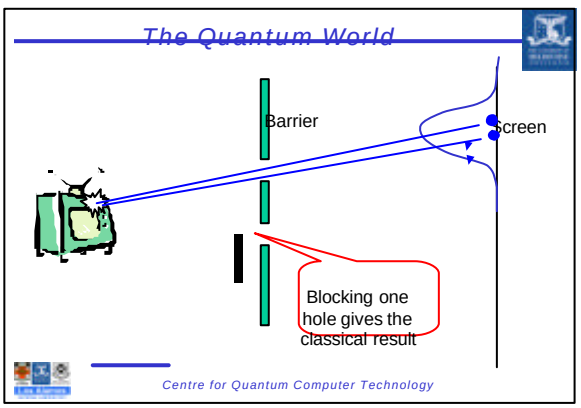
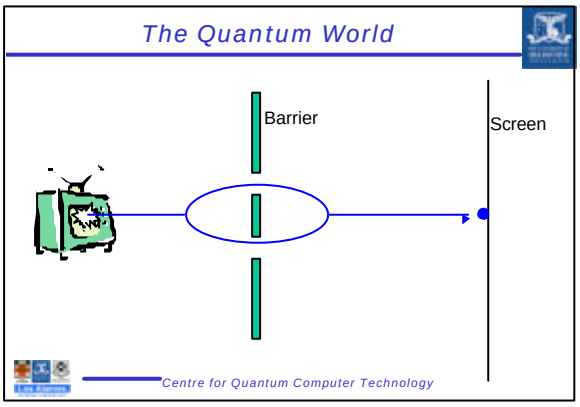

The Quantum World
Barrier
Screen
elslit
Centre for Quantum Computer Technology
Elslit1


The Quantum World
Barrier
Screen
Centre for Quantum Computer Technology
Youngstwo slit


The Quantum World
Barrier
Screen
Blocking one hole gives the classical result
Centre for Quantum Computer Technology


The Quantum World
Barrier
Screen
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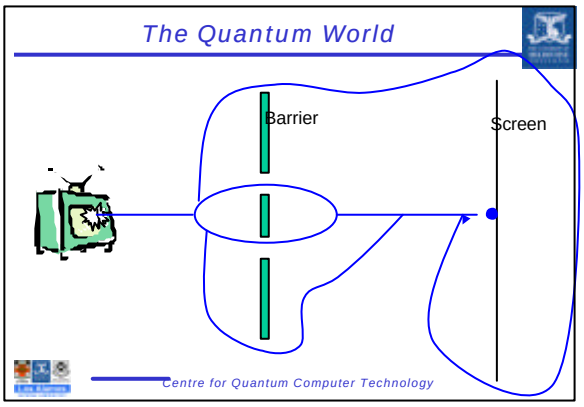
The Quantum World
Barrier
Screen
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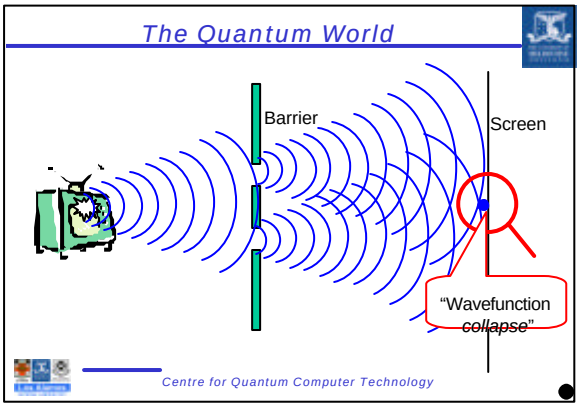
The Quantum World
Barrier
Screen
"Wavefunction collapse"
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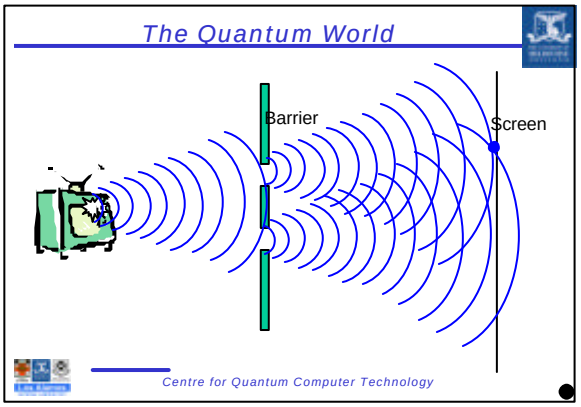
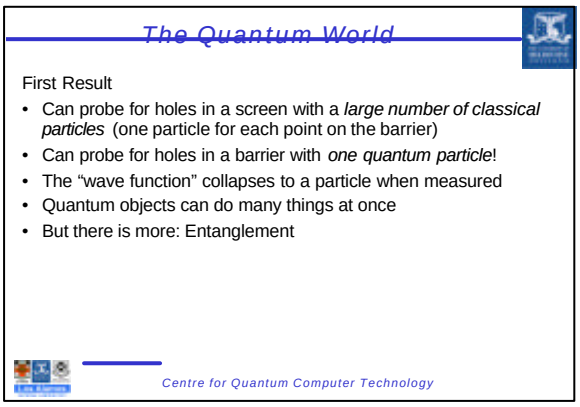

The Quantum World
Barrier
Screen
Centre for Quantum Computer Technology


The Quantum World
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
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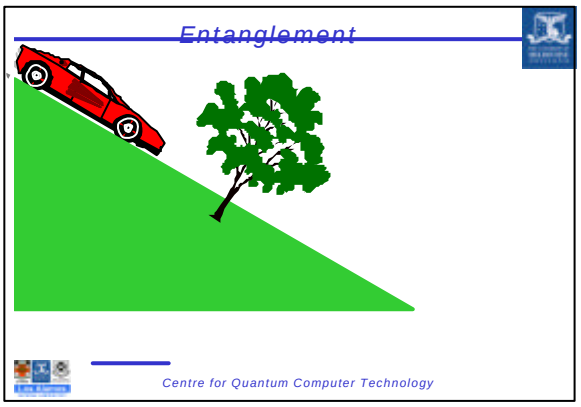
Entanglement
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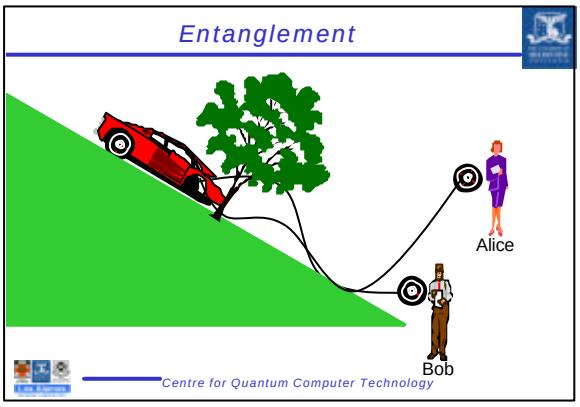
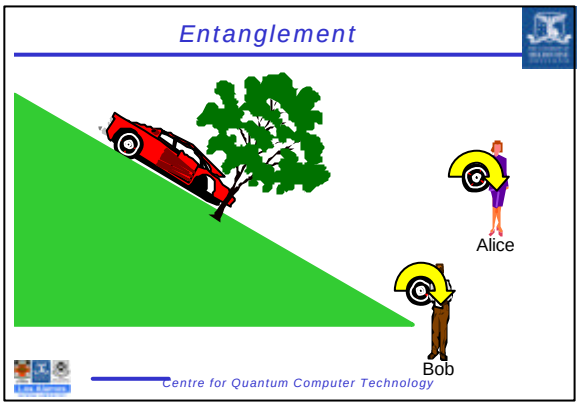
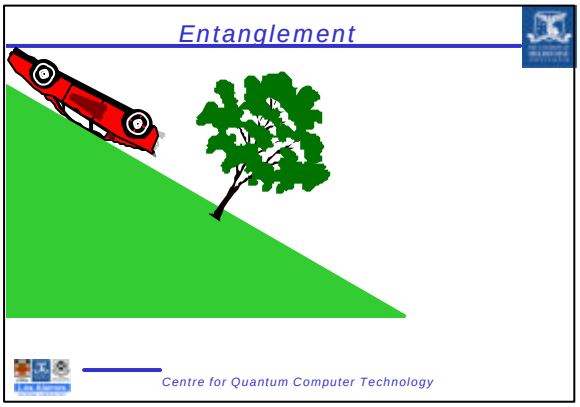
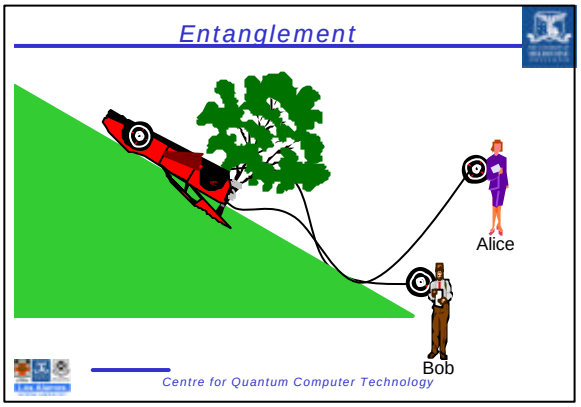
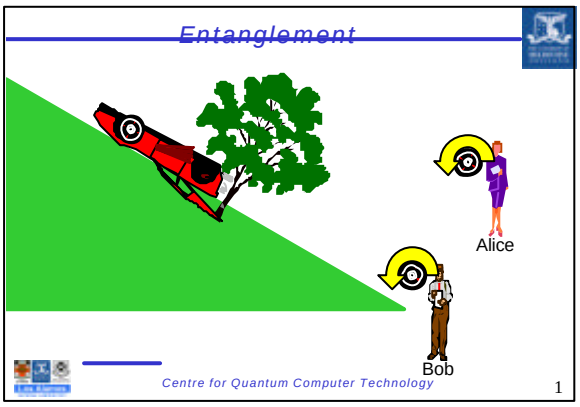
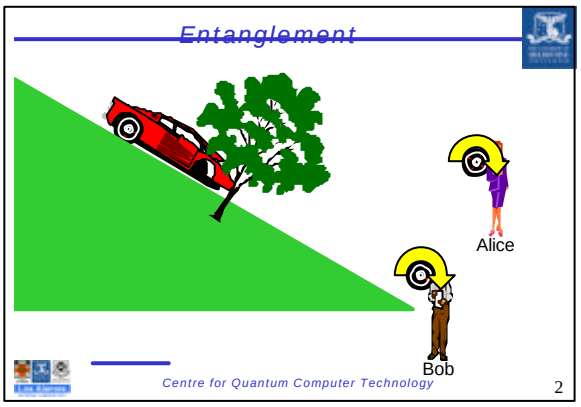

Entanglement
Alice
Bob
Centre for Quantum Computer Technology

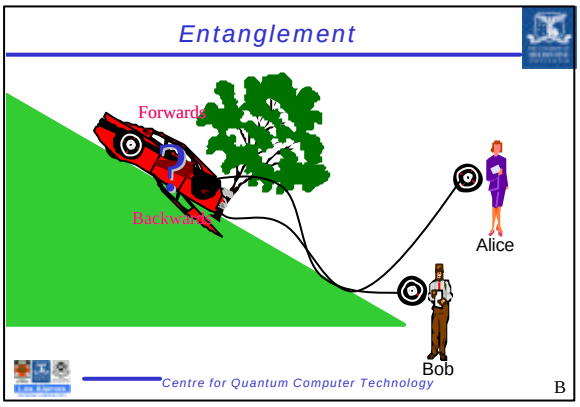

Entanglement
Alice
Bob
Centre for Quantum Computer Technology

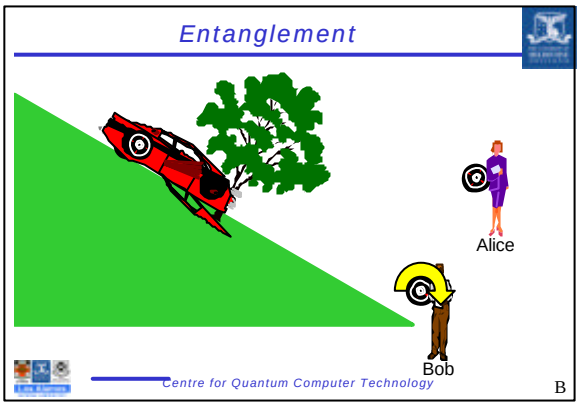

Entanglement
Centre for Quantum Computer Technology

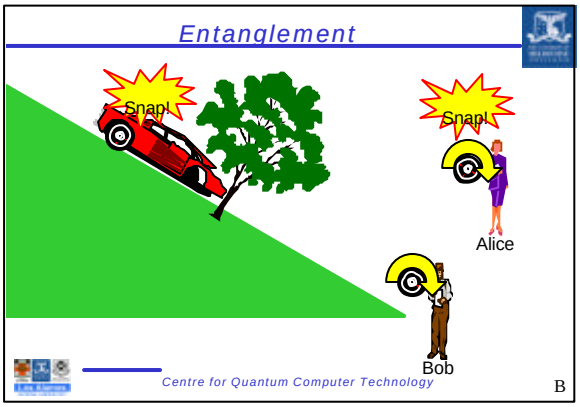

Entanglement
Alice
Bob
Centre for Quantum Computer Technology

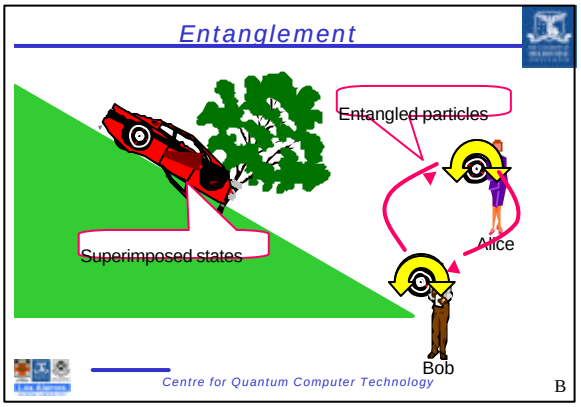

Entanglement
Alice
Bob
Centre for Quantum Computer Technology
1

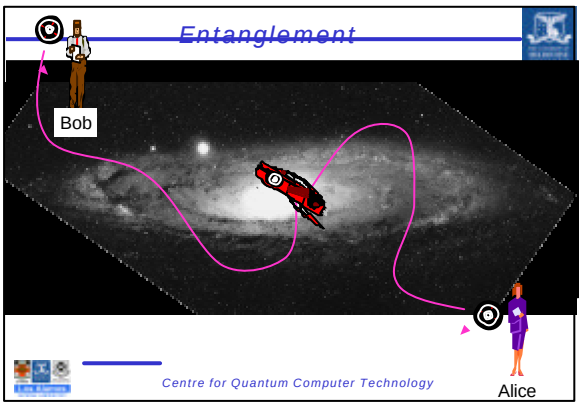

Entanglement
Alice
Bob
Centre for Quantum Computer Technology
2

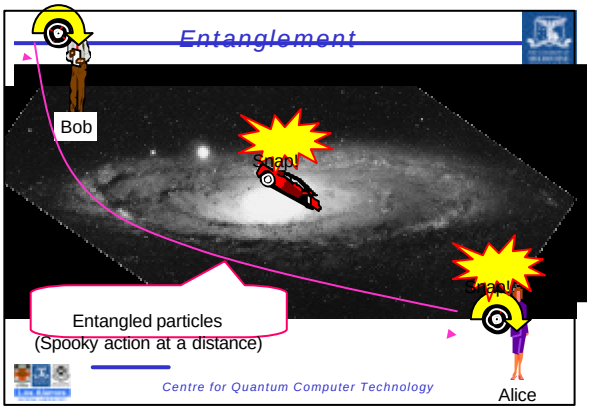

Entanglement
Forwards
Backwards
Alice
Bob
Centre for Quantum Computer Technology
B


Entanglement
Alice
Bob
Centre for Quantum Computer Technology
B


Entanglement
Snap!
Snap!
Alice
Bob
Centre for Quantum Computer Technology
B


Entanglement
Entangled particles
Superimposed states
Alice
Bob
Centre for Quantum Computer Technology
B


Entanglement
Bob
Centre for Quantum Computer Technology
Alice


Entanglement
Bob
Snap!
Snap!
Entangled particles
(Spooky action at a distance)
Centre for Quantum Computer Technology
Alice

The Quantum World

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...

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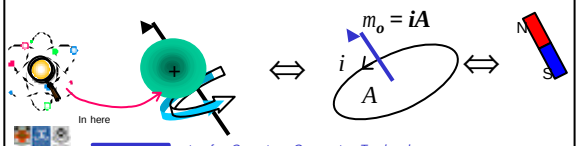
Spin

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



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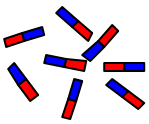
Spin and Magnetism

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



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Spin and Magnetism

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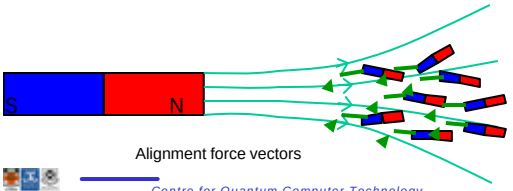

Alignment force vectors

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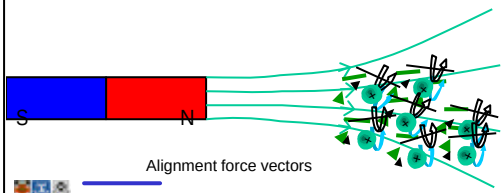
Magnets in box

Spin and Magnetism

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



Alignment force vectors

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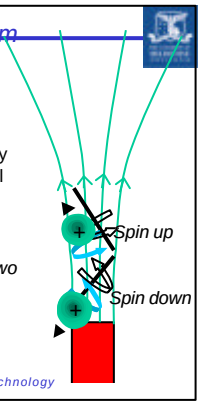
Spin and Magnetism

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)



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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

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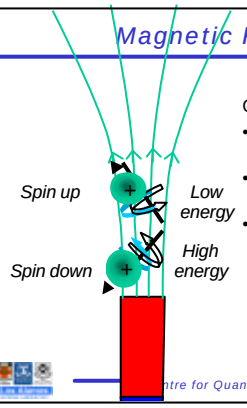
Magnetic Resonance



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)

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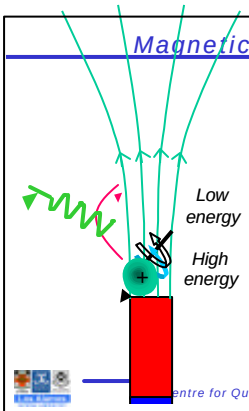
Classical magnet

Magnetic Resonance



Change orientations

- The high energy state will spontaneously relax back to the low energy state, releasing energy

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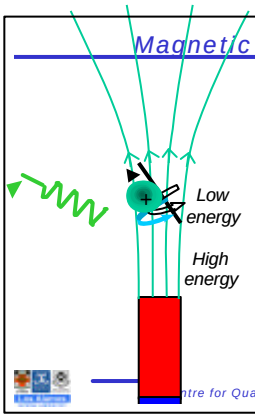
Magnetic Resonance



Change orientations

- The high energy state will spontaneously relax back to the low energy state, releasing energy

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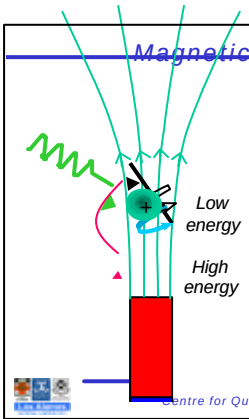
Magnetic Resonance



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*

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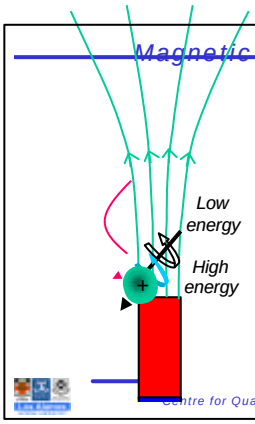
Magnetic Resonance



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

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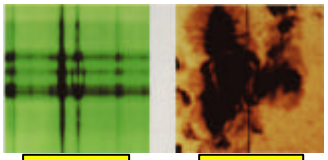
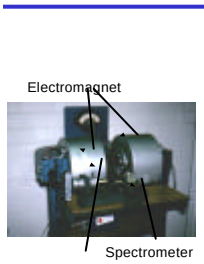
Magnetic Resonance: Zeeman Effect

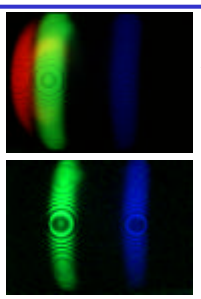
- Excited mercury vapour emits light owing to electrons jumping up and down between energy levels
- A magnetic field placed around the vapour splits the energy levels and causes small changes in the colour of the light
- These changes can be detected with a sensitive spectrometer
- Can also see the effect in sunspots...



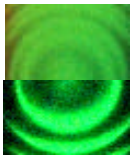
Spectrometer | Photograph

Zeeman effect in our labs



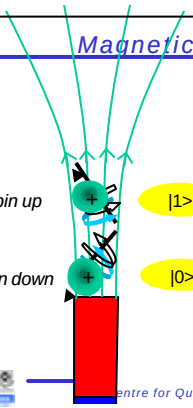


Strong field



No field

Magnetic Resonance



Assign qubits

Classical equivalents

Spin up |1> 1

Spin down |0> 0

|10>

(No classical equivalent! 1 and 0 simultaneously!)

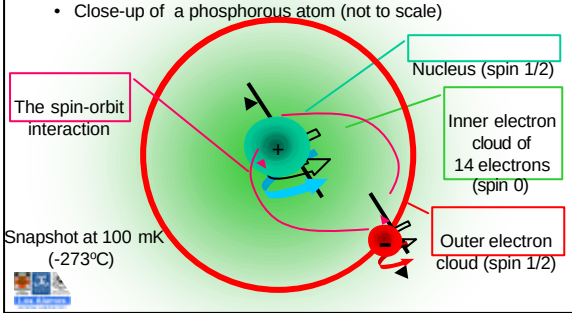
The Kane Quantum Computer

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}Si (spin-zero nucleus)
- Will use atoms of phosphorous (^{31}P) to carry the spins

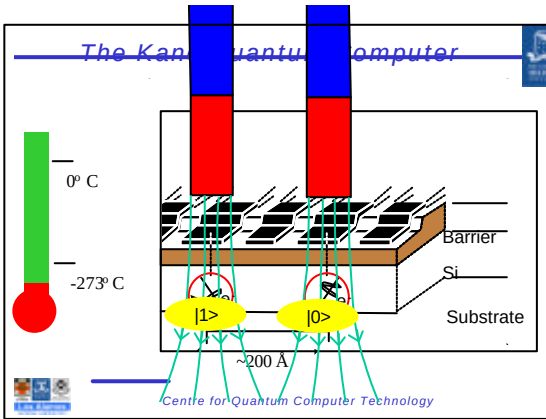
The Kane Quantum Computer

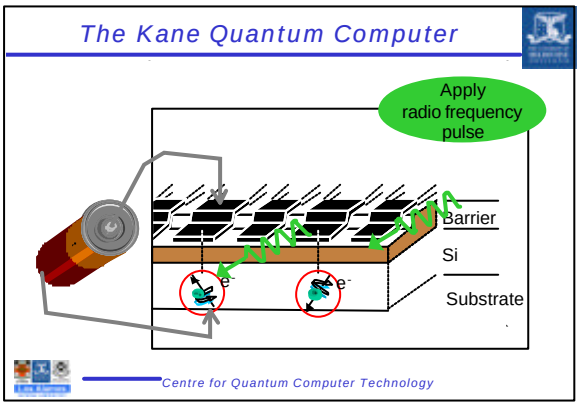
- Close-up of a phosphorous atom (not to scale)

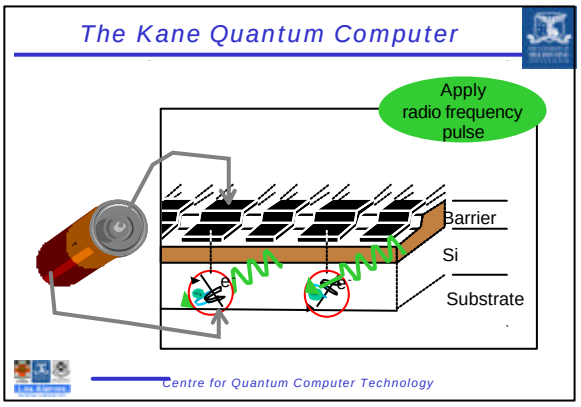


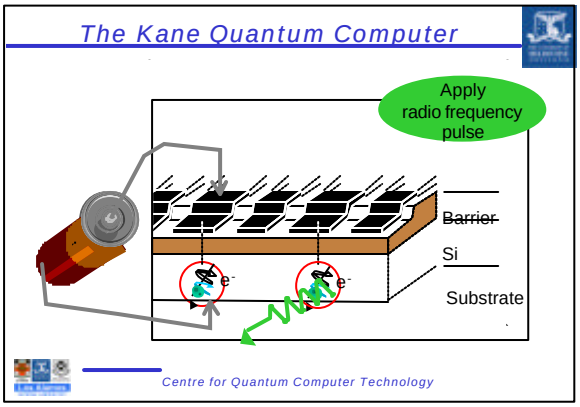
Snapshot at 100 mK (-273°C)

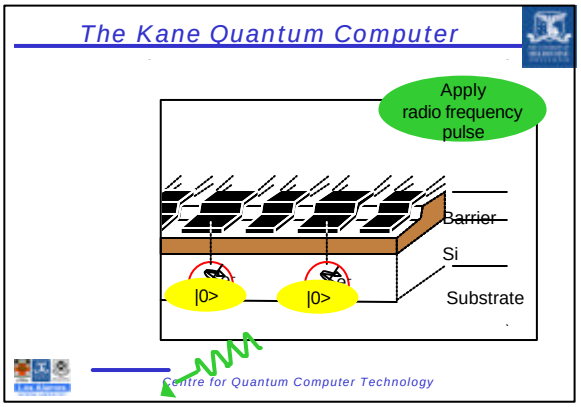
The Kane Quantum Computer

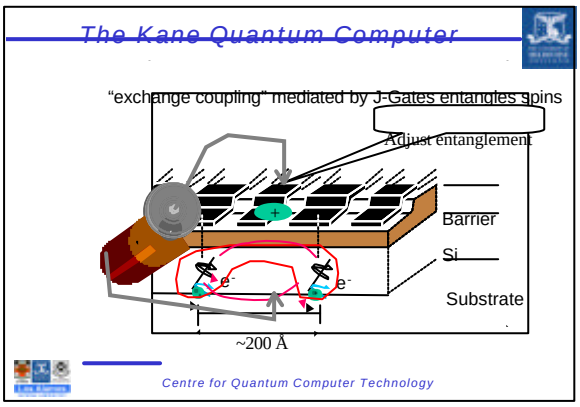


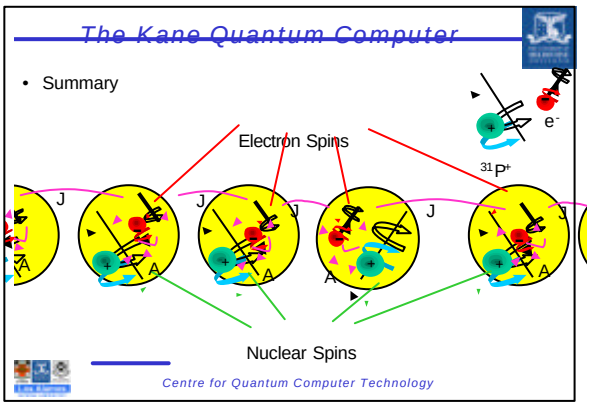

The Kane Quantum Computer
Apply radio frequency pulse
Barrier
Si
Substrate
e-
e-
Centre for Quantum Computer Technology


The Kane Quantum Computer
Apply radio frequency pulse
Barrier
Si
Substrate
e-
e-
Centre for Quantum Computer Technology


The Kane Quantum Computer
Apply radio frequency pulse
Barrier
Si
Substrate
e-
e-
Centre for Quantum Computer Technology


The Kane Quantum Computer
Apply radio frequency pulse
Barrier
Si
Substrate
|0>
|0>
Centre for Quantum Computer Technology


The Kane Quantum Computer
"exchange coupling" mediated by J-Gates entangles spins
Adjust entanglement
Barrier
Si
Substrate
e-
e-
~200 Å
Centre for Quantum Computer Technology


The Kane Quantum Computer
• Summary
Electron Spins
31P+
e-
J
A
Nuclear Spins
Centre for Quantum Computer Technology

Fabrication Pathways

Who is going to make this?

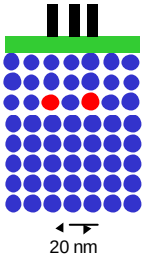
We are!

- 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

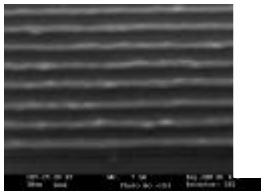
(1) Nano-scale Lithography



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

(1) Nano-scale Lithography

- Electron beam lithography at the University of New South Wales



Sub-300Å AuPd gates on GaAs

(1) Nano-scale Lithography

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

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

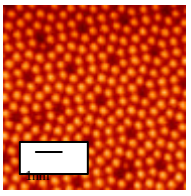


Image of individual atoms on silicon surface

(2) Alternative Fabrication Pathway

Difficulties:

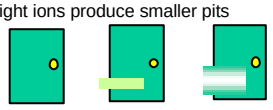
- Must place ^{31}P to a precision of a few billionths of a metre
- Having done that, need to come back and add metal electrodes on the buried ^{31}P atoms for the gates
- The ^{31}P must not move about while doing this

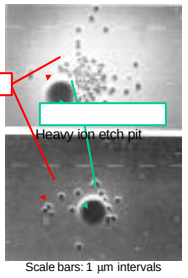
An alternative strategy:

- 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



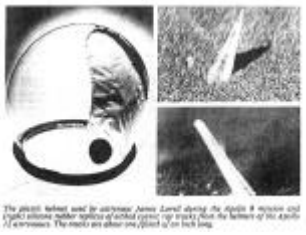


Scale bars: 1 µm intervals

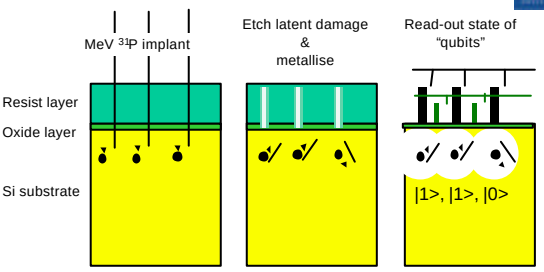
From: B.E. Fischer,Nucl. Instr. Meth. B54 (1991) 401.

Ion tracks in space

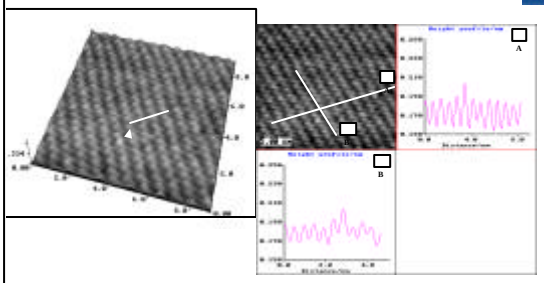
- Cosmic rays struck this Apollo 8 helmet made from CR-39 plastic
- Etching in NaOH revealed the tracks



(2) Direct ^{31}P ion implantation

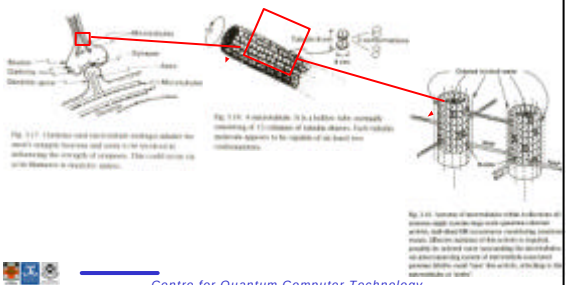


Key Technologies; Imaging a single interstitial P atom



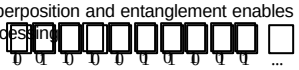
Is the human brain a quantum computer?

- Roger Penrose thinks so!



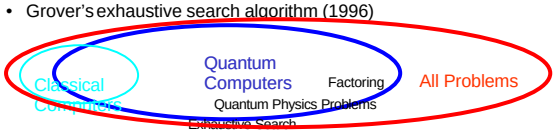
Conclusion: Quantum Computer

- Superposition and entanglement enables massive parallel processing



binary ***qubits***

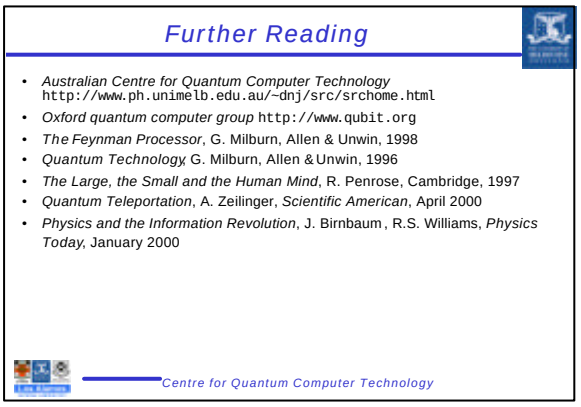
- (L qubits can store 2^L numbers at once, classical only 1)
- Shor's prime factorization algorithm (1994) relevant to cryptography
- Grover's exhaustive search algorithm (1996)



Conclusion: Quantum Computer

*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
http://www.ph.unimelb.edu.au/~dnj/src/srchome.html
Oxford quantum computer group http://www.qubit.org
The Feynman Processor, G. Milburn, Allen & Unwin, 1998
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. Birnbaum , R.S. Williams, Physics Today, January 2000
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