2000 July Lecture

QUANTUM COMPUTING: New beads on the abacus

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•Laser Physics Centre, Department of Physics, University of Queensland

•Microanalytical Research Centre, School of Physics, University of Melbourne

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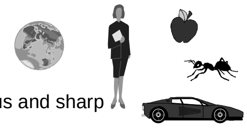
Classical Physics / Quantum Physics

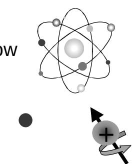
Classical Physics

- 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



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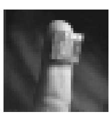
Classical computing: Moore's Law

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)

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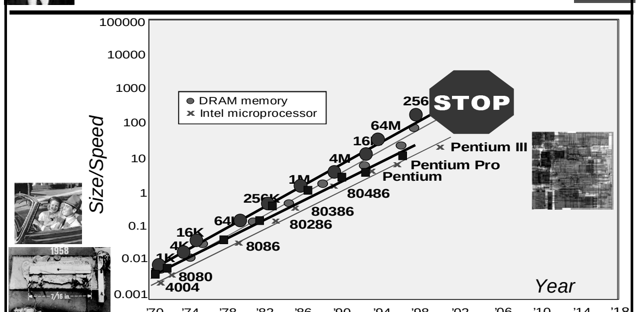
Ancient relics

The end of Moore's law



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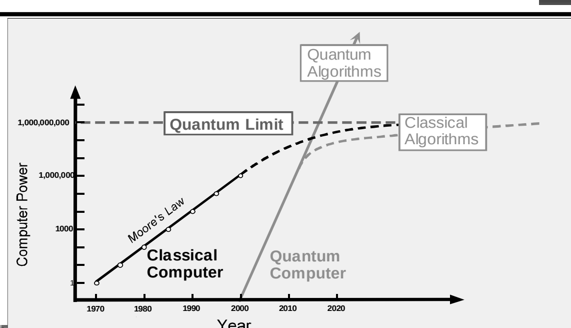
(Turn on sound)

The end of Moore's law?



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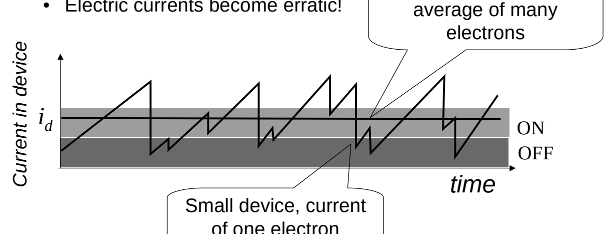
The end of Moore's Law!

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



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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

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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

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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?

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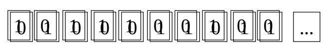
The Quantum Computer

Use quantum particles as the bits in a quantum computer!
- Conventional computer memory states:

1 0 1 1 1 0 0 1 1 0 ... 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?

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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

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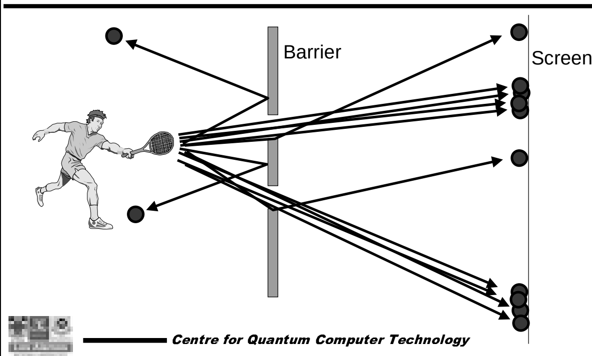
The Classical World



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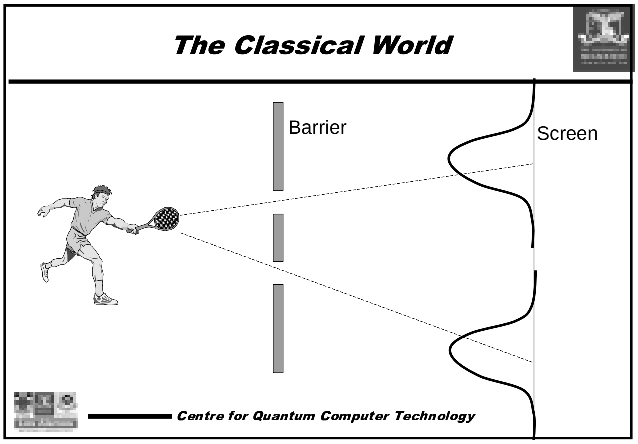
The Classical World
Barrier
Screen
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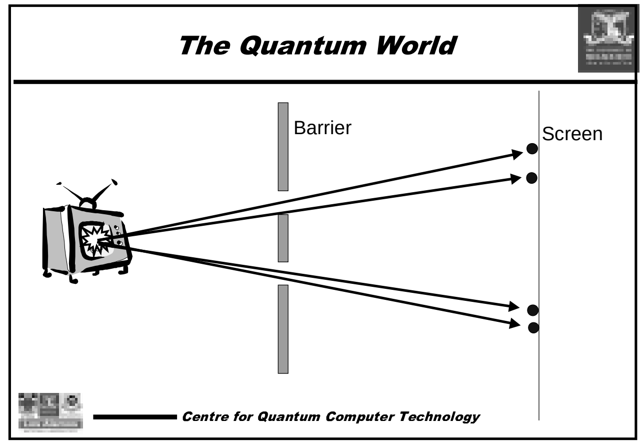
The Quantum World
Barrier
Screen
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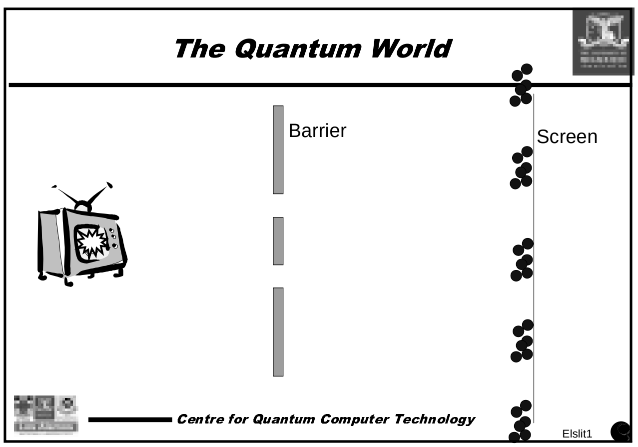
The Quantum World
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Screen
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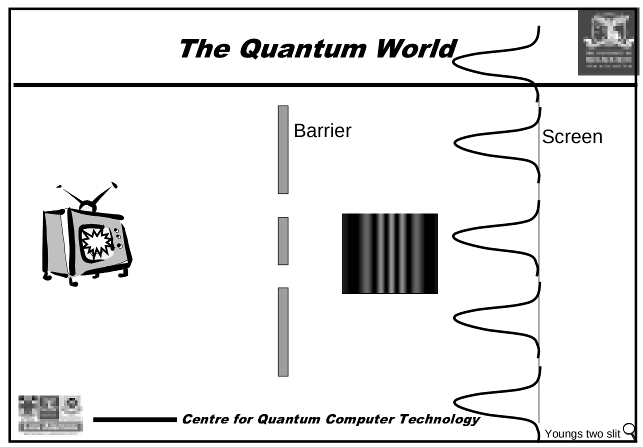
Elslit1


The Quantum World
Barrier
Screen
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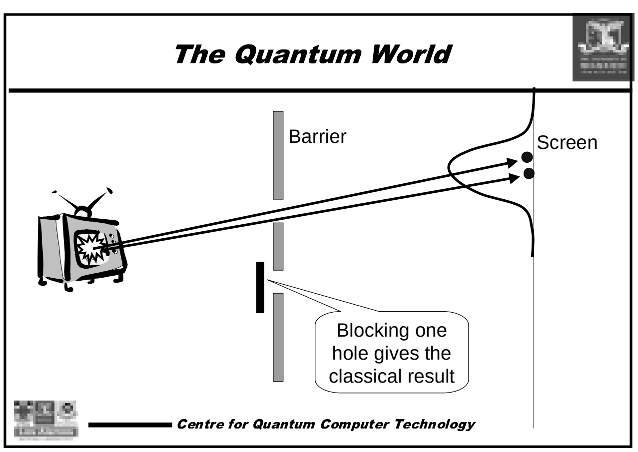
Youngs two slit


The Quantum World
Barrier
Screen
Blocking one hole gives the classical result
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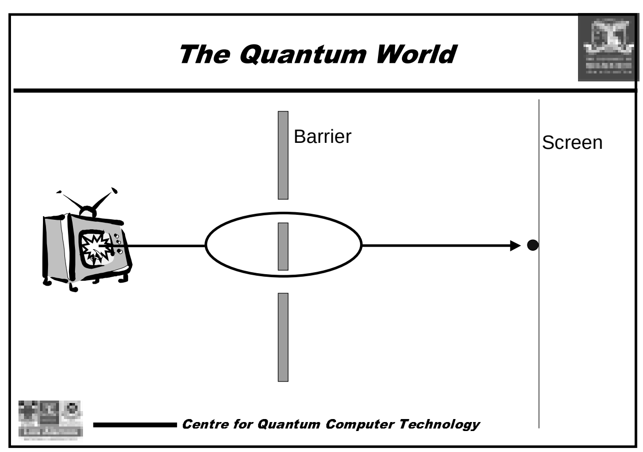
The Quantum World
Barrier
Screen
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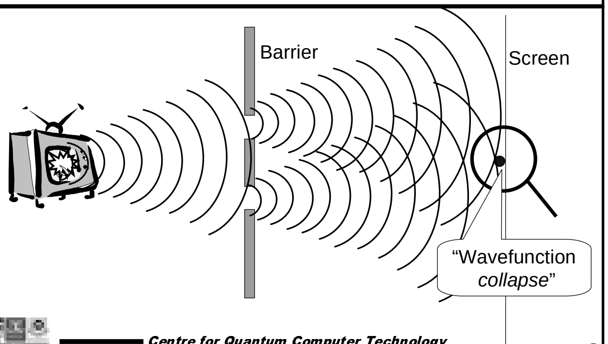
The Quantum World



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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 screen)
- Can probe for holes in a screen 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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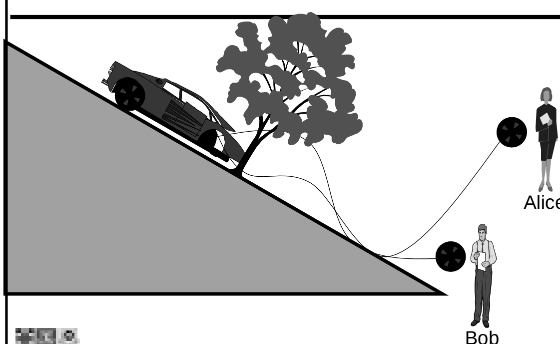
Entanglement



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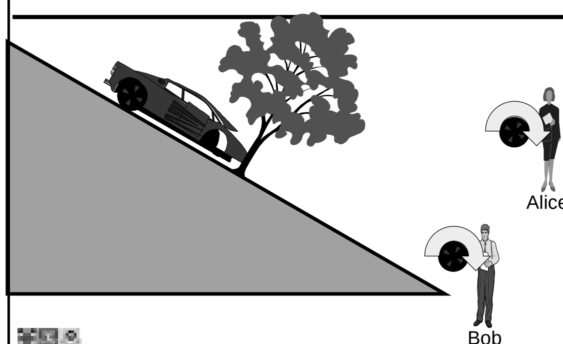
Entanglement



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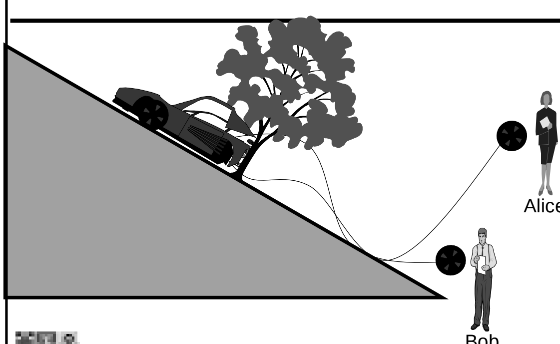
Entanglement



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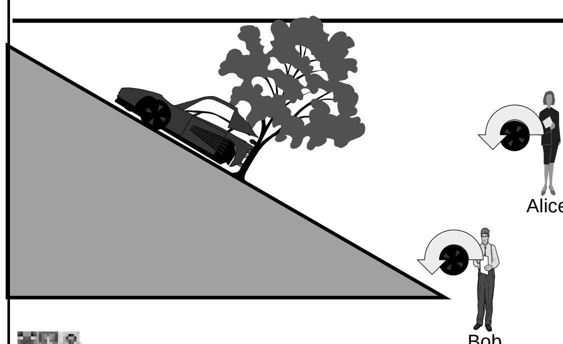
Entanglement



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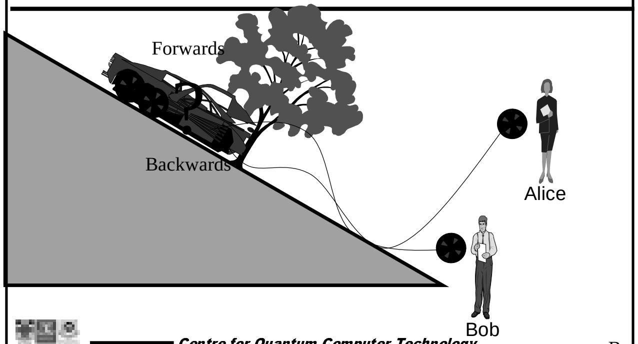
1

Entanglement



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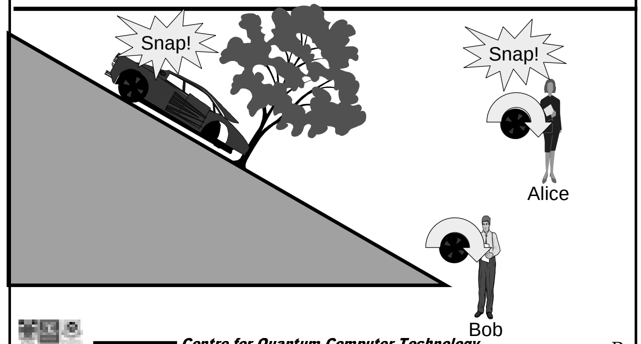
B

Entanglement



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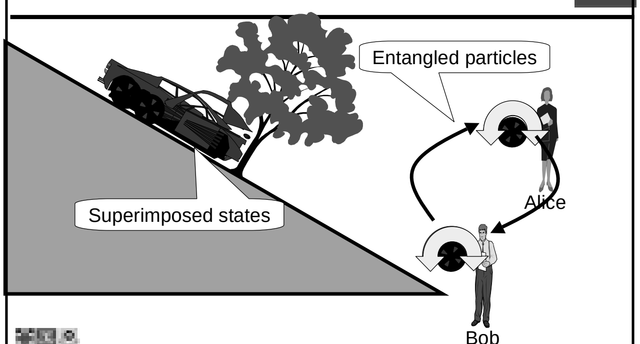
B

Entanglement



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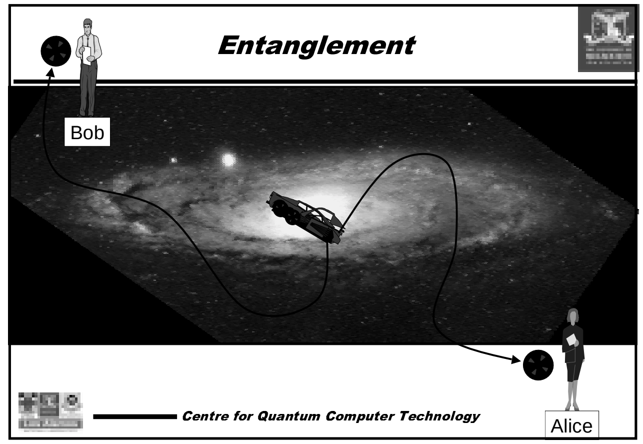
B

Entanglement



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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?

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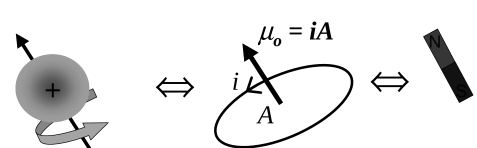
Magnetic Resonance

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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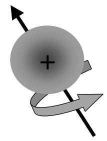
Magnetic Resonance

Magnetic moments

- The strength of the equivalent magnet depends of the "speed" of the spin and the "size" of the particle
- This is measured by the dipole moment, μ



Some examples:

Particle	Dipole moment, μ (Joule/Tesla)
Small Bar Magnet	5
Earth	8 x 10^{22}
Proton	1.4 x 10^{-26}
Neutron	(1/2.8)proton
Electron	9.3 x 10^{-24} = 660proton

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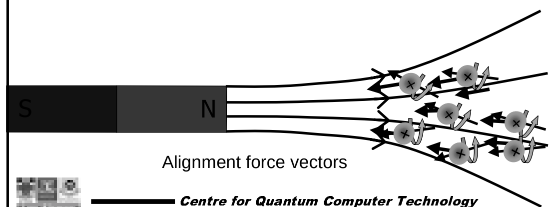
Magnetic Resonance

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



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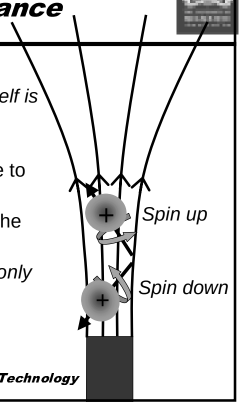
Magnetic Resonance

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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Magnetic Resonance

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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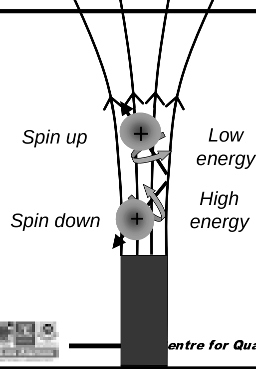
Magnetic Resonance



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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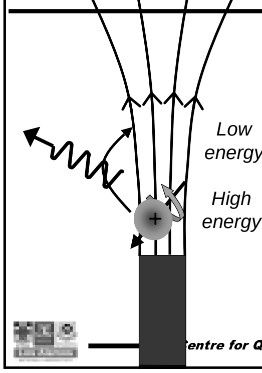
Classical magnet

Magnetic Resonance



Change orientations

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

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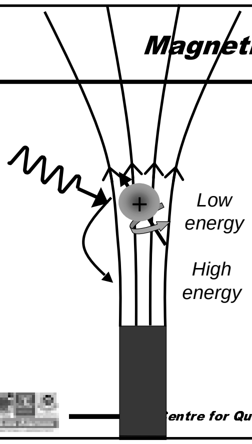
Magnetic Resonance



Change orientations

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

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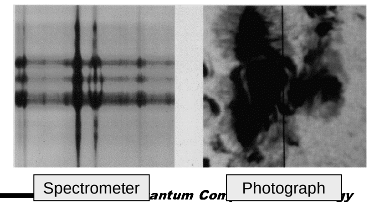
Magnetic Resonance: Zeeman Effect

- 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...



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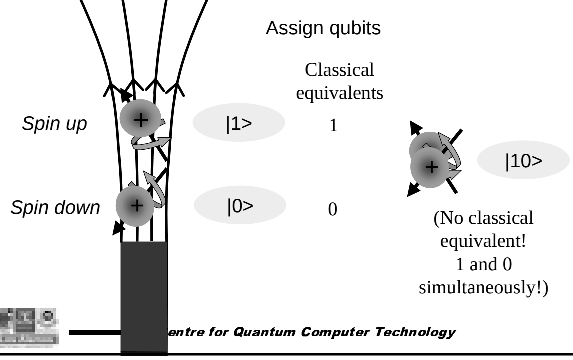
Zeeman Effect

Magnetic Resonance



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

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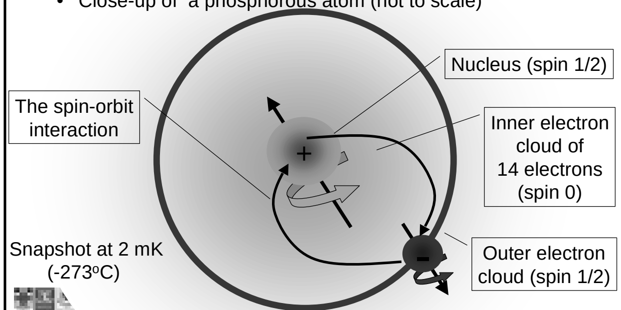
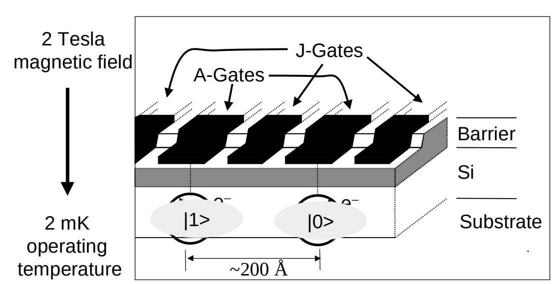
The Kane Quantum Computer

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



The Kane Quantum Computer



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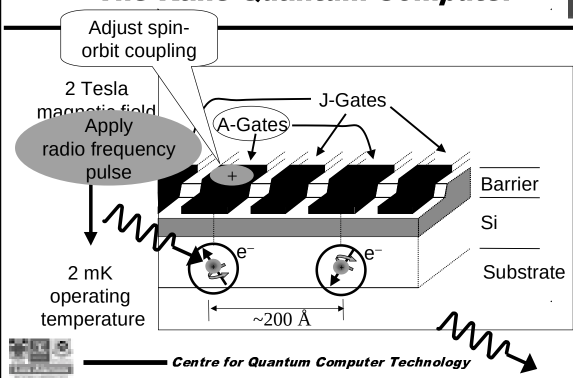
The Kane Quantum Computer



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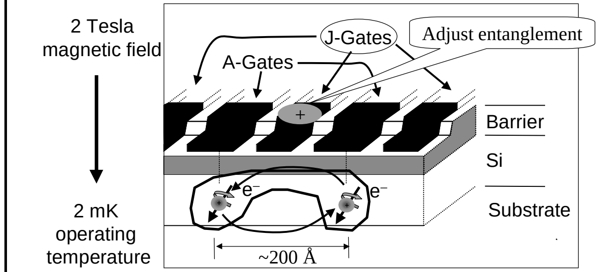
The Kane Quantum Computer

"exchange coupling" mediated by J-Gates entangles spins



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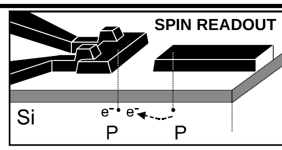
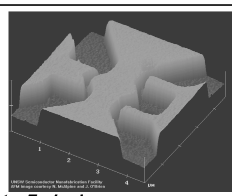
The Kane Quantum Computer

Operating sequence summary:

- Initialise nuclear spins by means of A-Gates and NMR pulses
- Commence "computation" by entangling nuclear spins through J-Gates and spin-orbit coupling
- Read final state of spins by means of a single electron transistor
- Final state is the equivalent to the diffraction pattern in the two slit experiment





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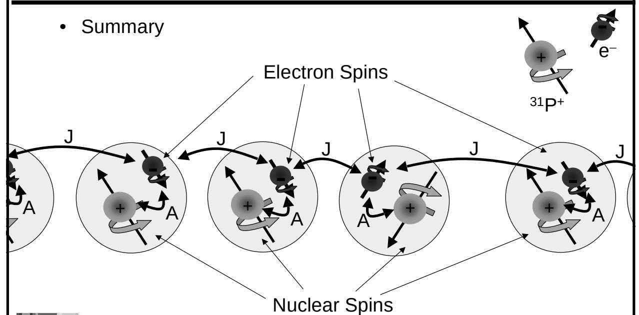
The Kane Quantum Computer

- Summary



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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

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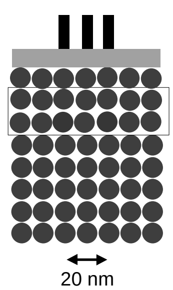
(1) Nano-scale Lithography



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

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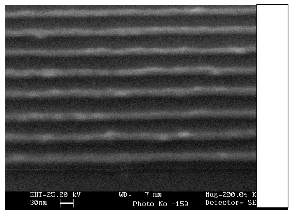
(1) Nano-scale Lithography

- Electron beam lithography at the University of New South Wales



Sub-300Å AuPd gates on GaAs

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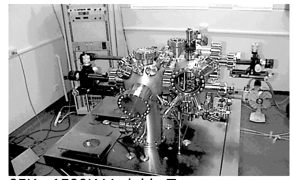
(1) Nano-scale Lithography

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



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

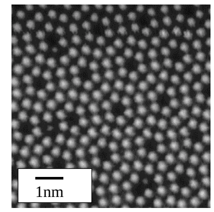


Image of individual atoms on silicon surface

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(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

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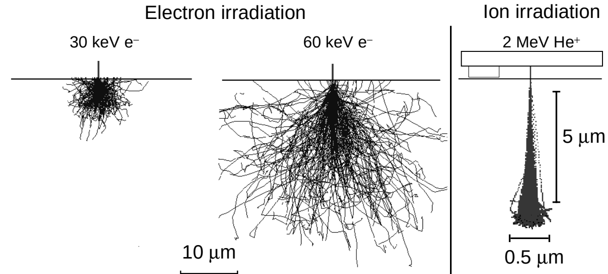
(2) Direct ^{31}P ion implantation



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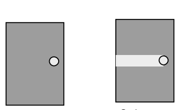
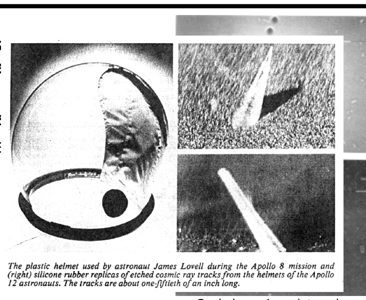
(2) Direct ^{31}P ion implantation

- Single MeV heavy ions produce latent damage
- Etching in NaOH devel damage to produce pit
- Light ions produce sma





The plastic helmet used by astronaut James Lovell during the Apollo 8 mission and (right) silicone rubber replicas of etched cosmic ray tracks from the helmets of the Apollo 12 astronauts. The tracks are about one-fiftieth of an inch long.

Scale bars: 1 μm intervals

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

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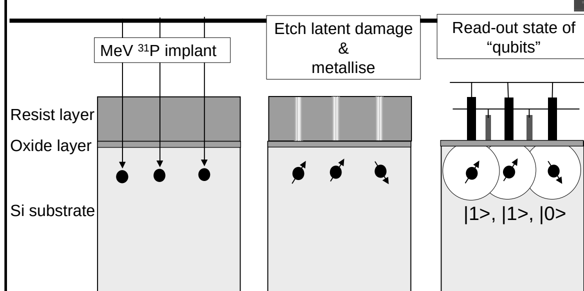
(2) Direct ^{31}P ion implantation



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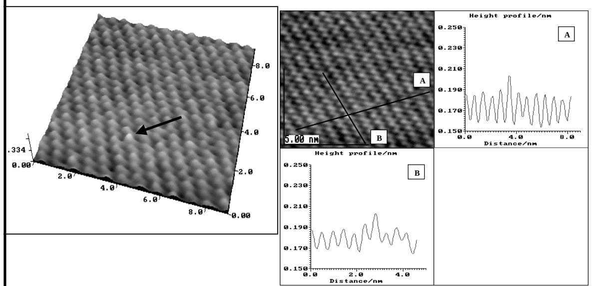
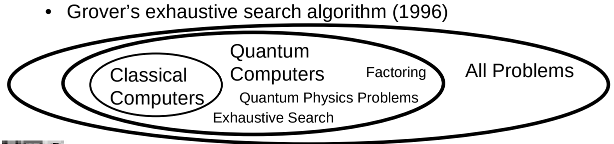
Key Technologies; Imaging a single interstitial P atom



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)



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