Quantum Computing

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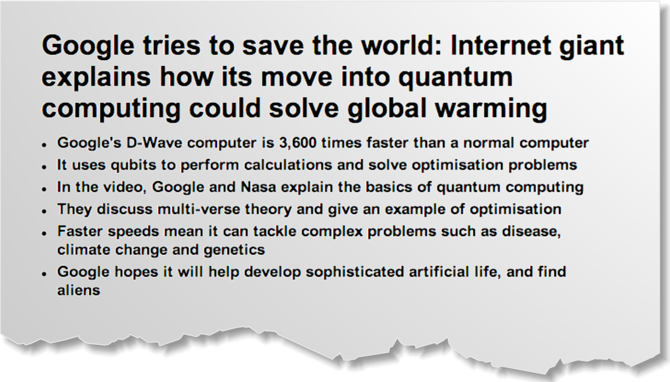

Google tries to save the world: Internet giant explains how its move into quantum computing could solve global warming

- Google's D-Wave computer is 3,600 times faster than a normal computer
- It uses qubits to perform calculations and solve optimisation problems
- In the video, Google and Nasa explain the basics of quantum computing
- They discuss multi-verse theory and give an example of optimisation
- Faster speeds mean it can tackle complex problems such as disease, climate change and genetics
- Google hopes it will help develop sophisticated artificial life, and find aliens

Daily Mail, 15 October 2013

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This talk

1. A brief introduction to the quantum computing model
2. Quantum algorithms: what quantum computers can do
3. Experimental implementations
4. Further reading

The quantum model: qubits

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Pic: coins-of-the-uk.co.uk

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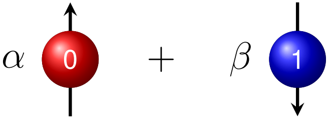
- A qubit ("quantum bit") is stored in a tiny physical system like an individual atom that behaves quantum mechanically.

The quantum model: qubits

As well as being in states corresponding to 0 or 1, a qubit can be anywhere in between!



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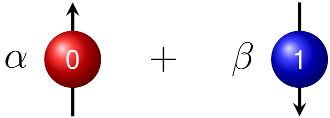

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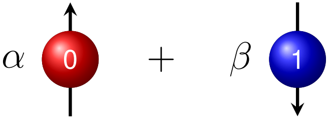

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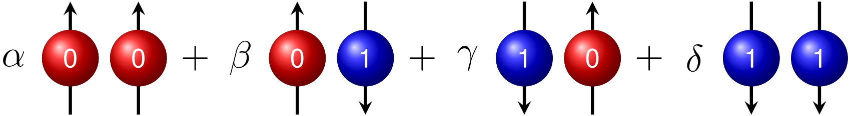
If we have n qubits, they can be in a superposition of 2^n different states:



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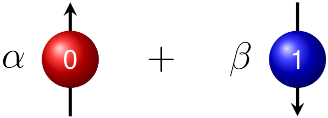

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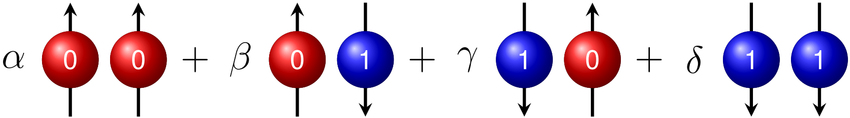

This allows a quantum computer to run an algorithm on many possible inputs simultaneously.

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University of BRISTOL

Measurement and entanglement

- If we measure some qubits, we see each outcome with probability equal to its corresponding coefficient squared.

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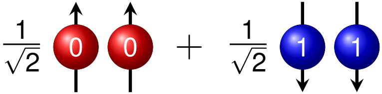

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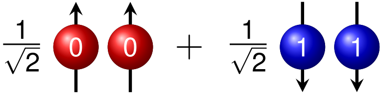

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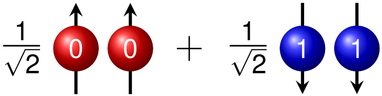

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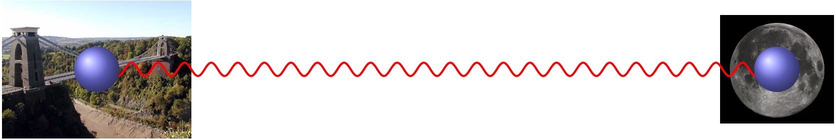
- But what if the first qubit is in Bristol, and the second is on the Moon?



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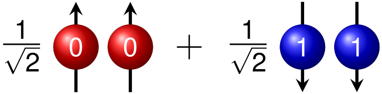

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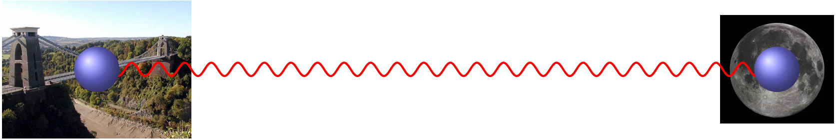

- It seems that the measurement result in Bristol has instantaneously affected the qubit on the Moon...
- This bizarre phenomenon is known as quantum entanglement.

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Shor's algorithm

Integer factorisation

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Shor's algorithm

- In 1994, Peter Shor described a quantum algorithm which can factorise large integers efficiently.
- No efficient classical algorithm is known for this problem.

Pic: physik.uni-graz.at

Factorisation and cryptography

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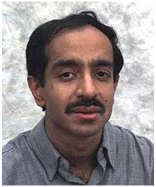
In 2009, a 232-digit number was factorised using hundreds of computers over a period of 2 years... by comparison, a large quantum computer could factorise a number with thousands of digits in a matter of minutes.

Grover's algorithm

- One of the most basic problems in computer science is unstructured search.



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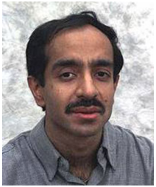

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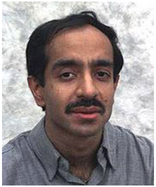

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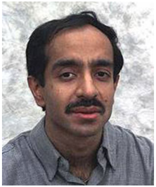
- On a classical computer, this task could require n queries in the worst case. But on a quantum computer, Grover's algorithm can solve the problem with roughly $\sqrt{n}$ queries.



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Experimental implementations

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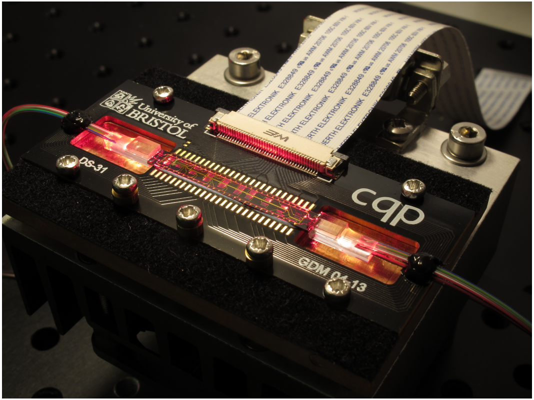

Photonic quantum circuits on silicon (University of Bristol)

Pic: University of Bristol

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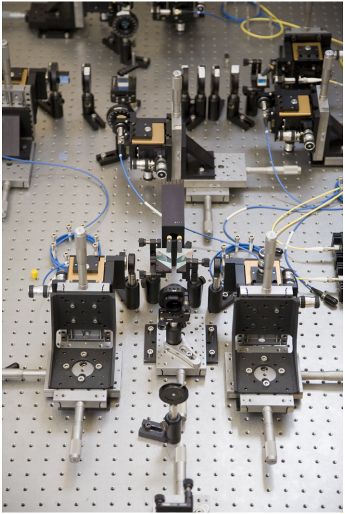
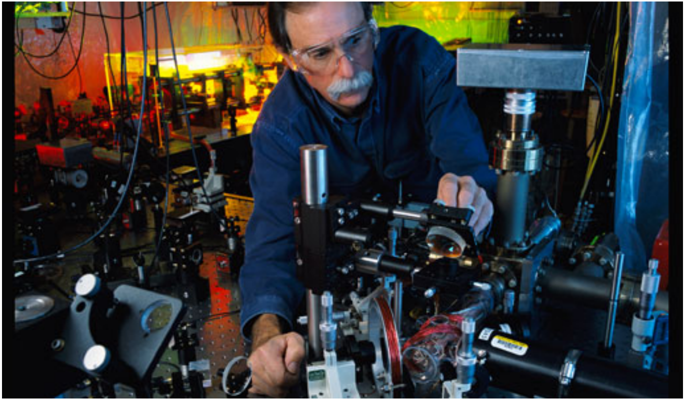


"Bulk" optics (University of Bristol)

Pic: Carmel King

Experimental implementations



Ion trap (David Wineland group, NIST)

Pic: nobelprize.org

Quantum computing FAQs

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To summarise:

- Quantum computing is a new and exciting model of computation which can do things that classical computing simply cannot.
- A massive international effort is ongoing to build a large-scale quantum computer, including here at Bristol.
- There are still many fascinating open problems to address.

Further reading

- Winning a Game Show with a Quantum Computer
  Ashley Montanaro
  `http://www.cs.bris.ac.uk/~montanar/gameshow.pdf`
- Quantum Computing Since Democritus
  Scott Aaronson
  `http://www.scottaaronson.com/democritus/`
- Introduction to Quantum Computing, University of Waterloo
  John Watrous
  `https://cs.uwaterloo.ca/~watrous/LectureNotes.html`

Partial timeline: Theory of quantum computing

	⋮
1984	Quantum cryptographic key distribution invented [Bennett+Brassard]
1985	General quantum computational model proposed [Deutsch]
1992	First exponential quantum speed-up discovered [Deutsch and Jozsa]
1993	Quantum teleportation invented [Bennett et al.]
1994	Shor’s algorithm rewrites the rulebook of classical cryptography
1995	Quantum error-correcting codes invented [Shor]
1996	Quantum simulation algorithm proposed [Lloyd]
1996	Quantum speed-up for unstructured search problems [Grover]
1998	Efficient quantum communication protocols [Buhrman et al.]
2003	Exponential speed-ups by quantum walks invented [Childs et al.]
	⋮

Partial timeline: Quantum computing experiments

	⋮
1997-8	Quantum teleportation demonstrated [Innsbruck, Rome, Caltech, . . .]
1998	Quantum error-correction demonstrated [MIT]
2001	Shor's algorithm factorises $15 = 3 \times 5$ using NMR [IBM]
2005	8 qubits controlled in ion trap [Innsbruck]
2008	Photonic waveguide quantum circuits demonstrated [Bristol]
2010	Entangled states of 14 qubits created in ion trap [Innsbruck]
2012	$21 = 3 \times 7$ factorised using quantum optics [Bristol]
2012	100μs coherence for superconducting electronic qubits [IBM]
2013	First publicly-accessible "quantum cloud" [Bristol]
	⋮