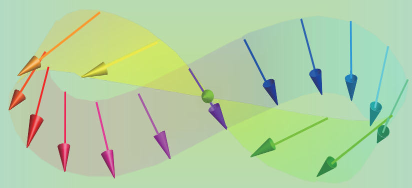
Nanoelectronics

18



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Department of Electronic Engineering

THE UNIVERSITY of York

12:00 Thursday, 16/March/2023 (P/T 005A)

Quick Review over the Last Lecture

Carbon nanomaterials :

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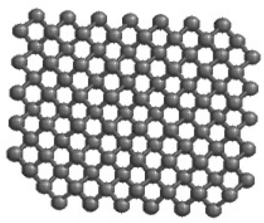

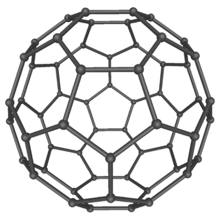

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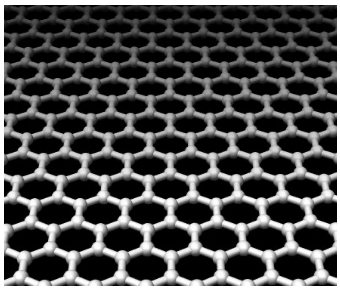
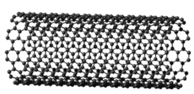




Contents of Nanoelectonics

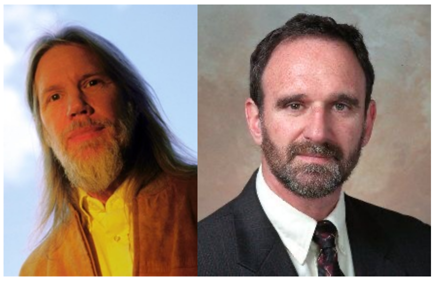
18 Quantum Computation

- Public key cryptosystem
- Traveling salesman problem
- Qubits

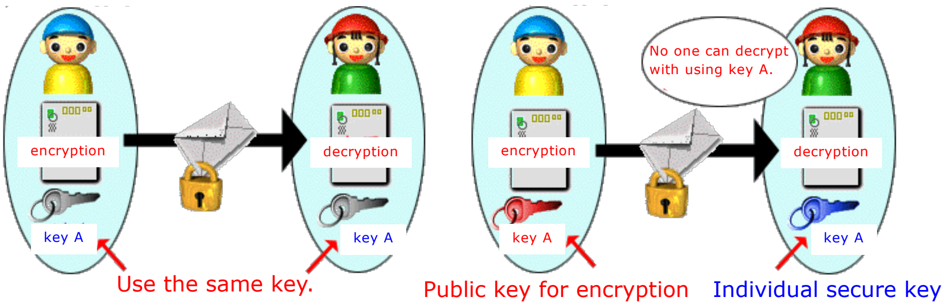
Public Key Cryptosystem

In 1976, B. Whitfield Diffie and Martin E. Hellman proposed public key cryptosystem.

RSA (Ronald L. Rivest, Adi Shamir and Leonard M. Adleman) cryptography developed in 1977.



Conventional cryptography



256-digit factorization : with IBM Blue Gene

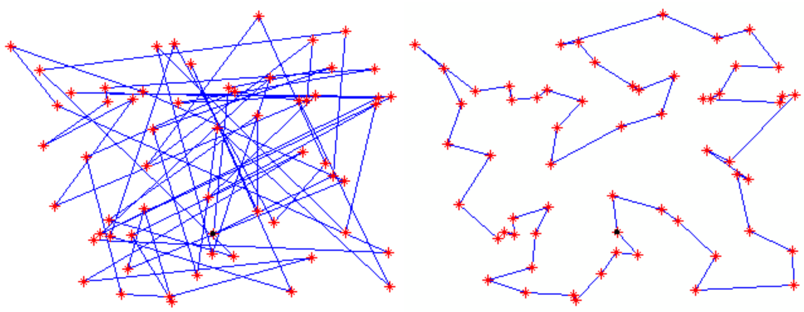
BUT ~ with a quantum computer !

* http://www.wikipedia.org/

** http://www.maitou.gr.jp/rsa/

Traveling Salesman Problem

As an example of non-deterministic polynomial (NP) complete problems :



* http://www.wikipedia.org/

Bee Can Solve a Traveling Salesman Problem

guardian.co.uk

Bees' tiny brains beat computers, study finds

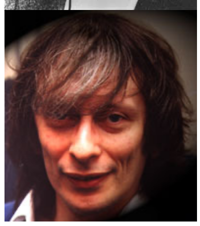
Bees can solve complex mathematical problems which keep computers busy for days, research has shown

- In pictures: Why the decline in bees matters
- Fears for crops as shock figures from America show scale of bee catastrophe

Press association
guardian.co.uk, Sunday 24 October 2010 21.45 BST

Researchers found that bees could solve the 'travelling salesman's' shortest route problem, despite having a brain the size of a grass seed. Photograph: Rex Features

History of Quantum Computation



In 1956, Richard P. Feynman told :

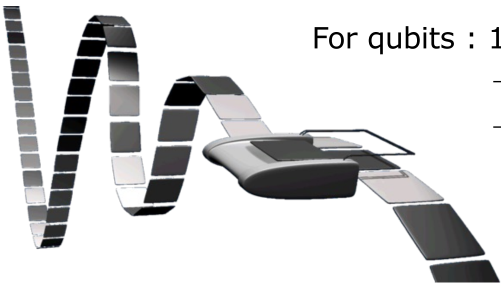
"There's plenty of room at the bottom."

In 1980, Paul Benioff predicted :

calculations without energy consumption
→ quantum computation

In 1985, David Deutch introduced quantum turing machine.

Turing machine : Input tape with letters



For qubits : 1 tape insertion
→ 2^n calculations achieved
→ parallel calculation

In 1994, Peter W. Shor formulated factorization algorithm.

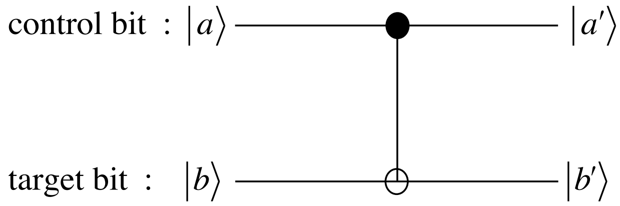
In 1996, L. K. Grover developed database algorithm.

* http://www.wikipedia.org/
** K. Nakamura, *SX World* **26**, Autumn (2000).

Technical Requirements for a Quantum Computer

5 major technical obstacles for the realisation of a quantum computer : *

- Array of necessary numbers of qubits
  - Factorization of a 200-digit integer → 1000 qubits
- Initialisation of qubits
  - $|0\rangle \otimes \cdots \otimes |0\rangle$
- Long coherence time
  - Q-factor = coherence time / 1 gate time > 10,000
- Operationability of a quantum logic gate
  - 1-qubit unitary transformation + 2-qubit CNOT gate



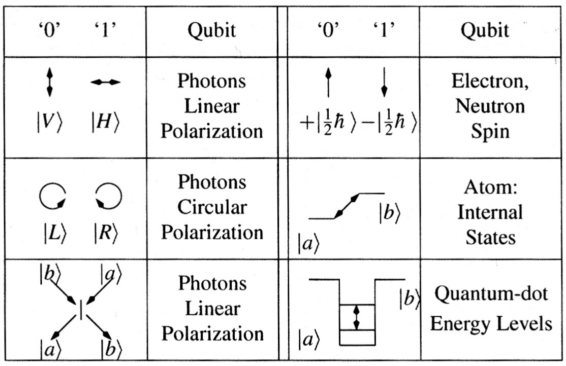
$\|a\rangle$	$\|b\rangle$	$\|a'\rangle$	$\|b'\rangle$
$\|0\rangle$	$\|0\rangle$	$\|0\rangle$	$\|0\rangle$
$\|0\rangle$	$\|1\rangle$	$\|0\rangle$	$\|1\rangle$
$\|1\rangle$	$\|0\rangle$	$\|1\rangle$	$\|1\rangle$
$\|1\rangle$	$\|1\rangle$	$\|1\rangle$	$\|0\rangle$

- Observability of qubits

* S. Kawabata, *NRI Res. Rep.* **1**, 4 (2004).

Potential Qubits

Major potential qubits for quantum computation :

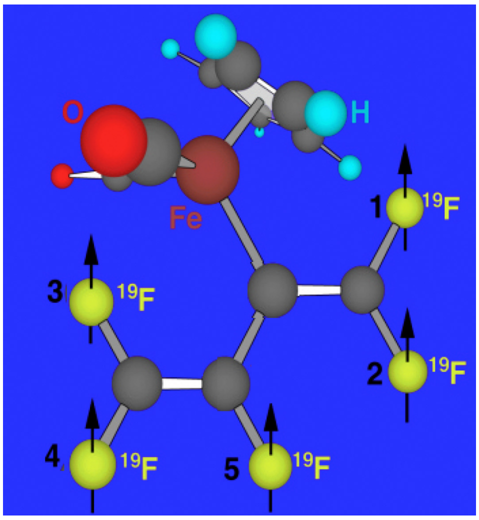


Qubits	Q-factor	Present records	Notes
Nuclear magnetic resonance (NMR)	10^{9}	7 qubits (algorithm)	Maximum 10 qubits
Ion-trap	10^{12}	2 qubits (algorithm)	Difficult to integrate
Superconducting charge	10^{4}	2 qubits (control NOT)	
Superconducting flux	10^{3}	1 qubit (unitary transformation)	
Exciton (electron-hole pair)	10^{3}	2 qubits (control NOT)	
Electron charge	10^{5}	1 qubit (unitary transformation)	
Electron spin	10^{4}		
Nuclear spin	10^{9}		

* K. Goser, P. Glösekötter and J. Dienstuhl, *Nanoelectronics and Nanosystems* (Springer, Berlin, 2004).
** S. Kawabata, *NRI Res. Rep.* **1**, 4 (2004).

NMR Qubits

5-qubit operation at 215 Hz was achieved :

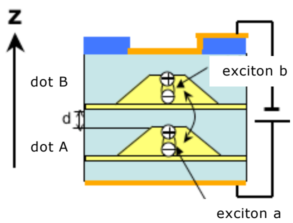


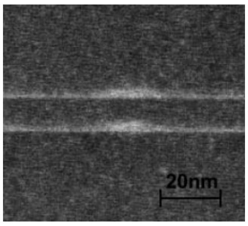
Maximum 10 qubits ...

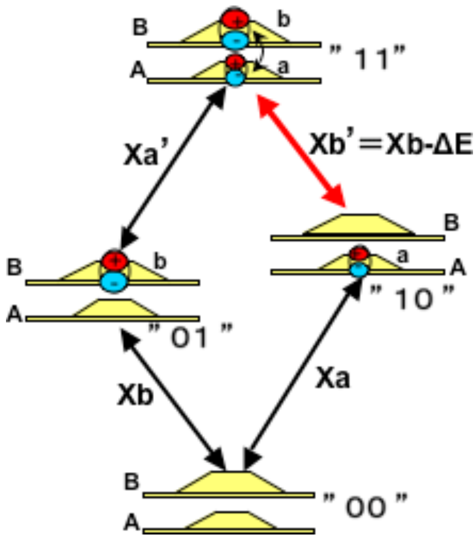
* L. M. K. Vandersypen *et al*., *Phys. Rev. Lett*. **85**, 5452 (2000).

Exciton Qubits in Solid States

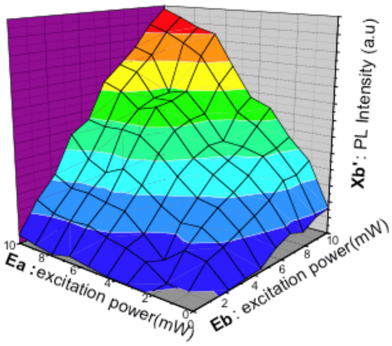
InAs quantum dots buried in GaAs act as qubits :







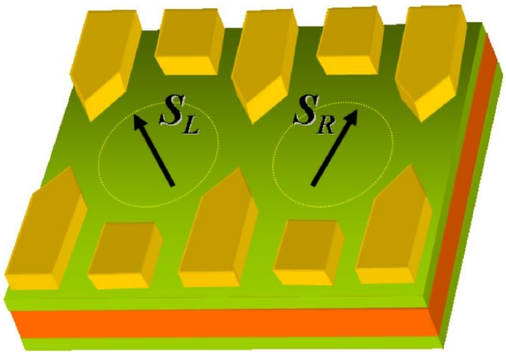
2-qubit state "1 1"



* K. Goshima *et al*., *Appl. Phys. Lett*. **87**, 253110 (2005).

Spin Qubits in Solid States

In 1998, Daniel Loss and David P. DiVincenzo proposed spin qubits :



Qubits : electron spins embedded in quantum dots

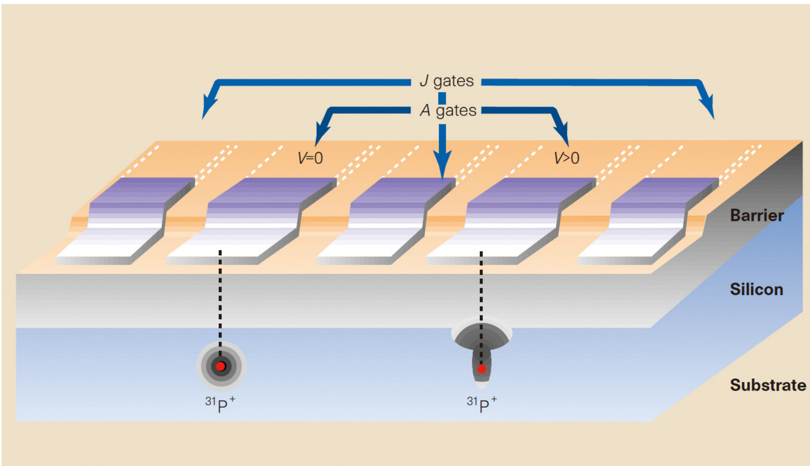
Unitary transformation : application of an external magnetic field

Control NOT : Heisenberg interaction between neighbouring spins

* http://theorie5.physik.unibas.ch/loss/
** http://www.rle.mit.edu/60th/speakers.htm
*** http://www.wikipedia.org/

Nuclear Spin Qubits in Solid States

In 1998, Bruce E. Kane proposed nuclear spin qubits doped in Si :



Advantage : very long coherence time (10^6 sec at ~100 mK)

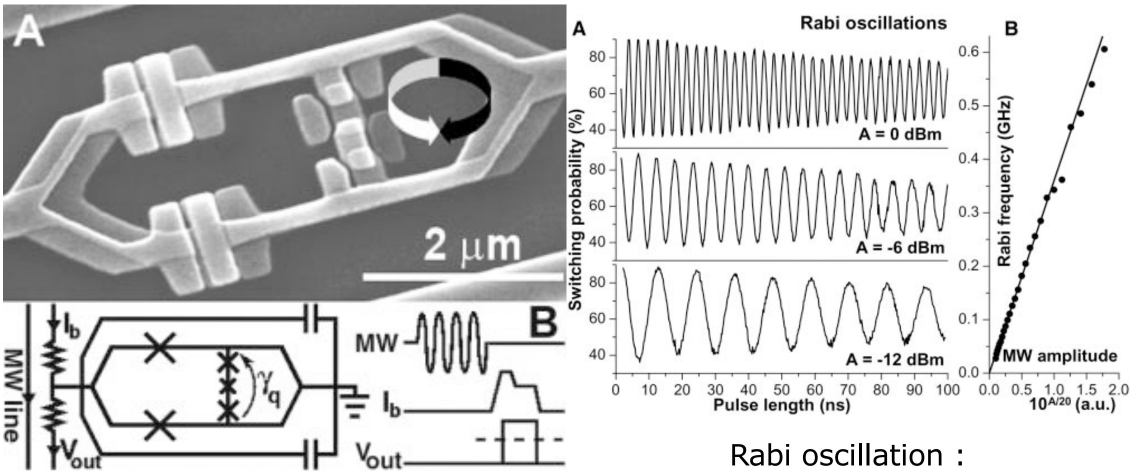
By applying gate *A* voltage, P^+ and an electron in an *A* gate couples → polarises.

J gate controls the interaction between the neighbouring nuclear spins.

* D. P. DiVincenzo, *Nature* **393**, 113 (1998).

Superconducting Qubits in Solid States

In 1999, first demonstration of 1-qubit unitary transformation in solid states :



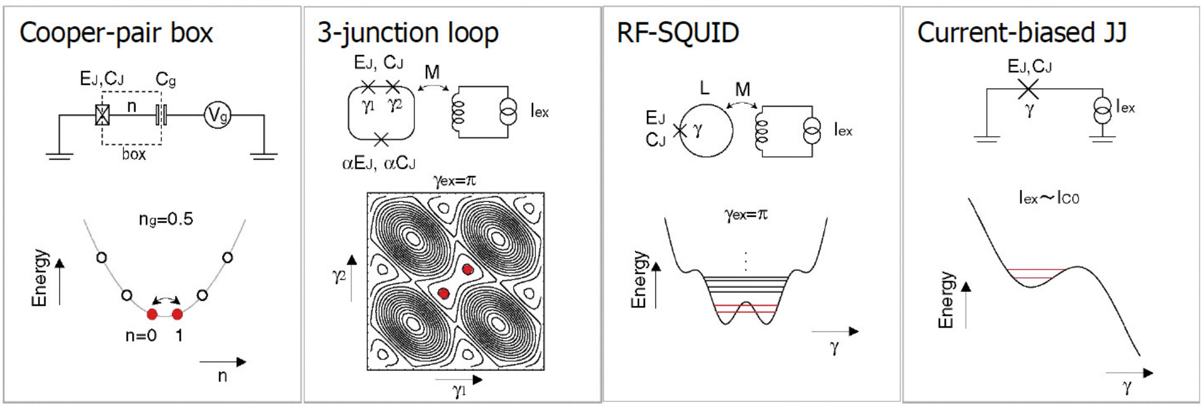
Rabi oscillation :
Proof of quantum entanglement

* Y. Nakamura *et al.*, *Nature* **398,** 876 (1999); I. Chiorescu *et al.*, *Science* **299**, 1869 (2003).

Other Superconducting Qubits

small ← E_J/E_C → large

charge	phase (flux)	phase (flux)	phase



NEC Tsukuba Chalmers/Yale Saclay	Delft/NEC MIT NTT Jena	IBM Watson Stony Brook Rochester Rome	Kansas NIST Boulder Maryland
coherent/Rabi osc. Ramsey, echo	Rabi osc. Ramsey, echo	coherent osc.	Rabi osc.

* http://www3.fed.or.jp/salon/houkoku/re_ryoushi.pdf

Roadmap for Quantum Computation

D-Wave & ARDA Hardware Roadmaps

D-Wave Roadmap | **ARDA Roadmap**

# Entangled Qubits	# Qubits QFT	Year	ARDA Milestone
"1"	-	2002	
2	-	2003	
4	2	2004	
8	4	2005	
16	8	2006	
32	16	2007	3-5 qubits entangled; 2-qubit gates[1]
64	32	2008	
		2009	
		2010	
		2011	
		2012	10 or more qubits entangled

[1] Already completed for charge (published), underway for 3J, Saclay & CBJJ qubits.

http://www.dwavesys.com/ http://googleresearch.blogspot.jp/2013/05/launching-quantum-artificial.html

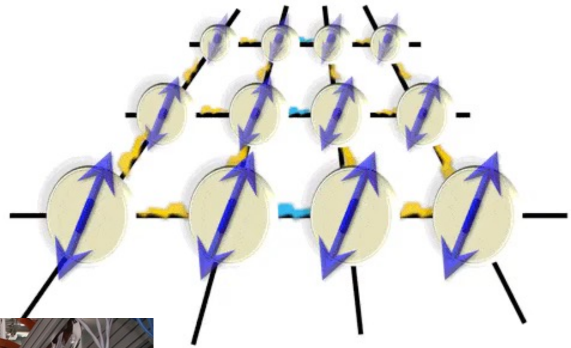
* http://www3.fed.or.jp/salon/2ndryo/2ndryo_houkokusho_.pdf

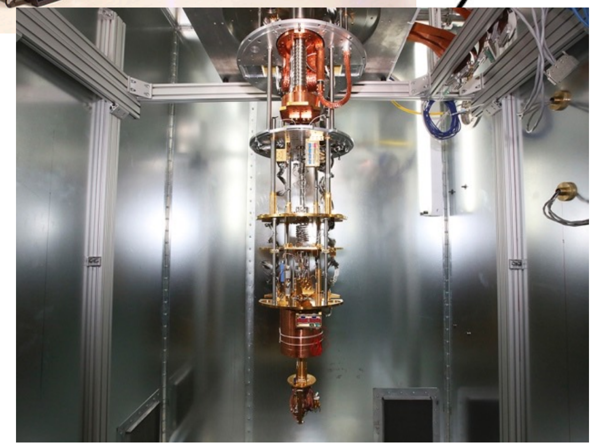
Quantum Annealing

* https://www.youtube.com/watch?v=UV_RlCAc5Zs

Latest Model from D-Wave

In 2017, D-Wave introduced a 2,000 qubit system with quantum annealing :

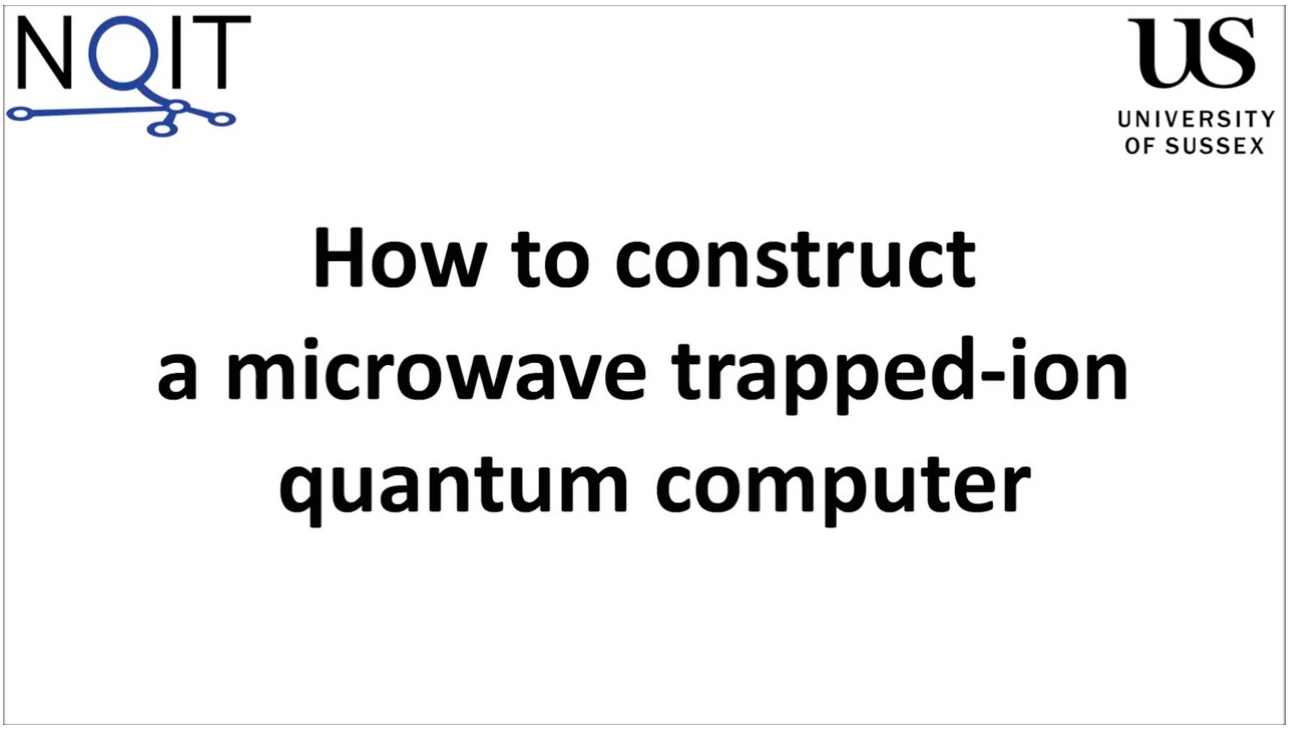




* E. Gibney, *Nature* **541**, 447 (2017);
** http://codezine.jp/article/detail/9491

Blueprint from the University of Sussex

In 2017, Sussex group proposed a trapped-ion quantum computer :



* https://www.youtube.com/watch?v=LZdJBIpryMw

Quantum Cryptosystem

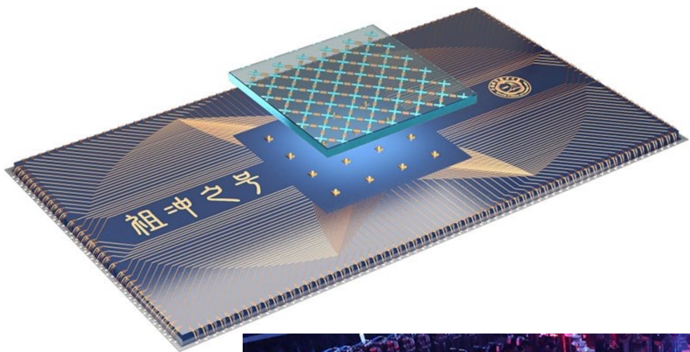
TU Darmstadt and NIST initiated a call for cryptosystem using quantum computation :

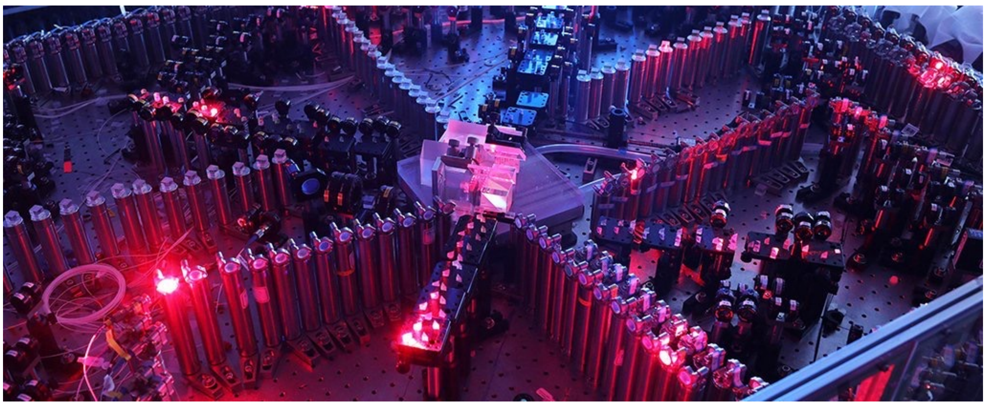
* https://www.latticechallenge.org

** https://csrc.nist.gov/Projects/Post-Quantum-Cryptography/Round-1-Submissions

Latest Quantum Computer

University of Science and Technology of China and QuantumCTek demonstrated 66 qubits with 113 photons : *





* Y. Wu *et al.*, *Phys. Rev. Lett.* **127**, 180501 (2021);

** https://www.sciencealert.com/china-s-latest-56-qubit-computer-marks-another-quantum-milestone

Trapped Ion Quantum Computer

Ionq introduced a quantum computer based on trapped ions : *

* https://ionq.com; https://www.youtube.com/watch?v=yvzU748e0V4

AI Chips

1.4 trillion transistors on a chip : *

	WSE 2	WSE	Nvidia A100
Size	46,225 mm^2	46,225 mm^2	826 mm^2
Transistors	2.6 trillion	1.2 trillion	54.2 billion
Cores	850,000	400,000	7,344
On-chip memory	40 gigabytes	18 GB	40 megabytes
Memory bandwidth	20 petabytes/s	9 PB/s	155 GB/s
Fabric bandwidth	220 petabits/s	100 Pb/s	600 gigabytes/s
Fabrication process	7 nm	16 nm	7 nm

* https://spectrum.ieee.org/cerebras-giant-ai-chip-now-has-a-trillions-more-transistors