How to build a universal quantum computer

John JL Morton
UCL

Quantum spin dynamics

LCN LONDON CENTRE FOR NANOTECHNOLOGY

UCL

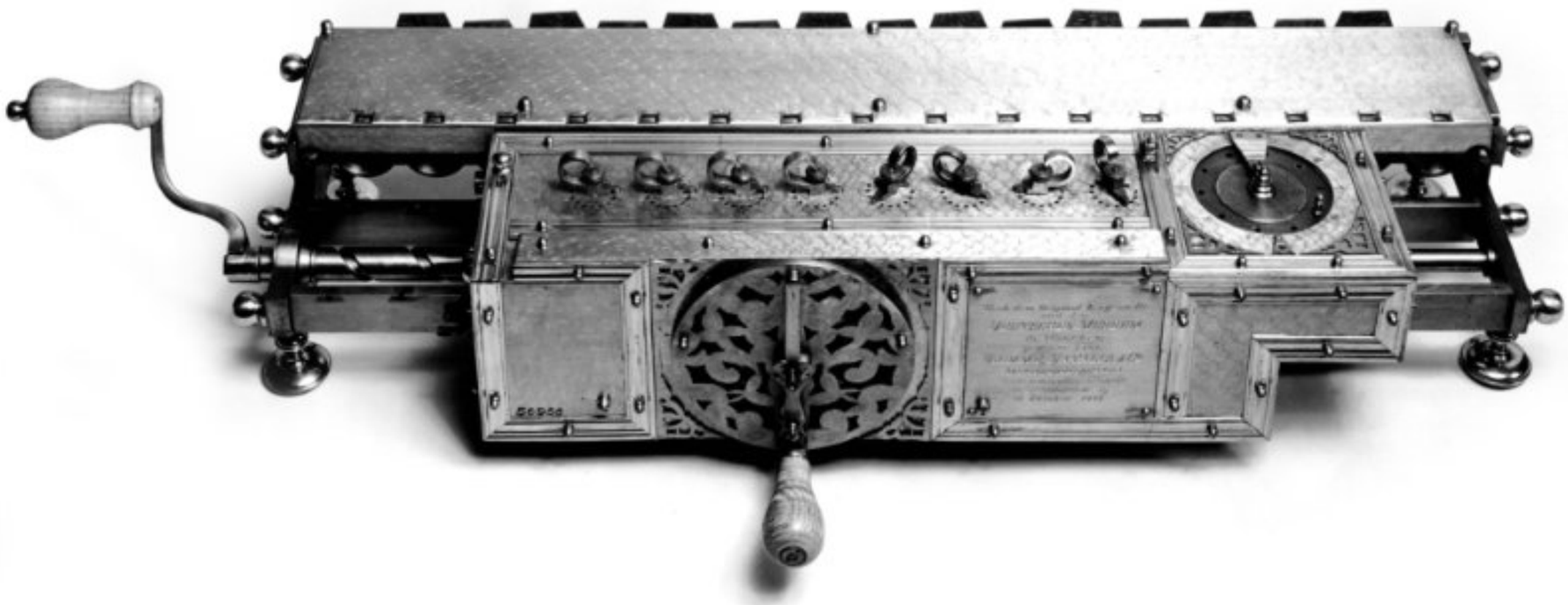
THE ROYAL SOCIETY

erc

1.

How to build a universal quantum computer ?

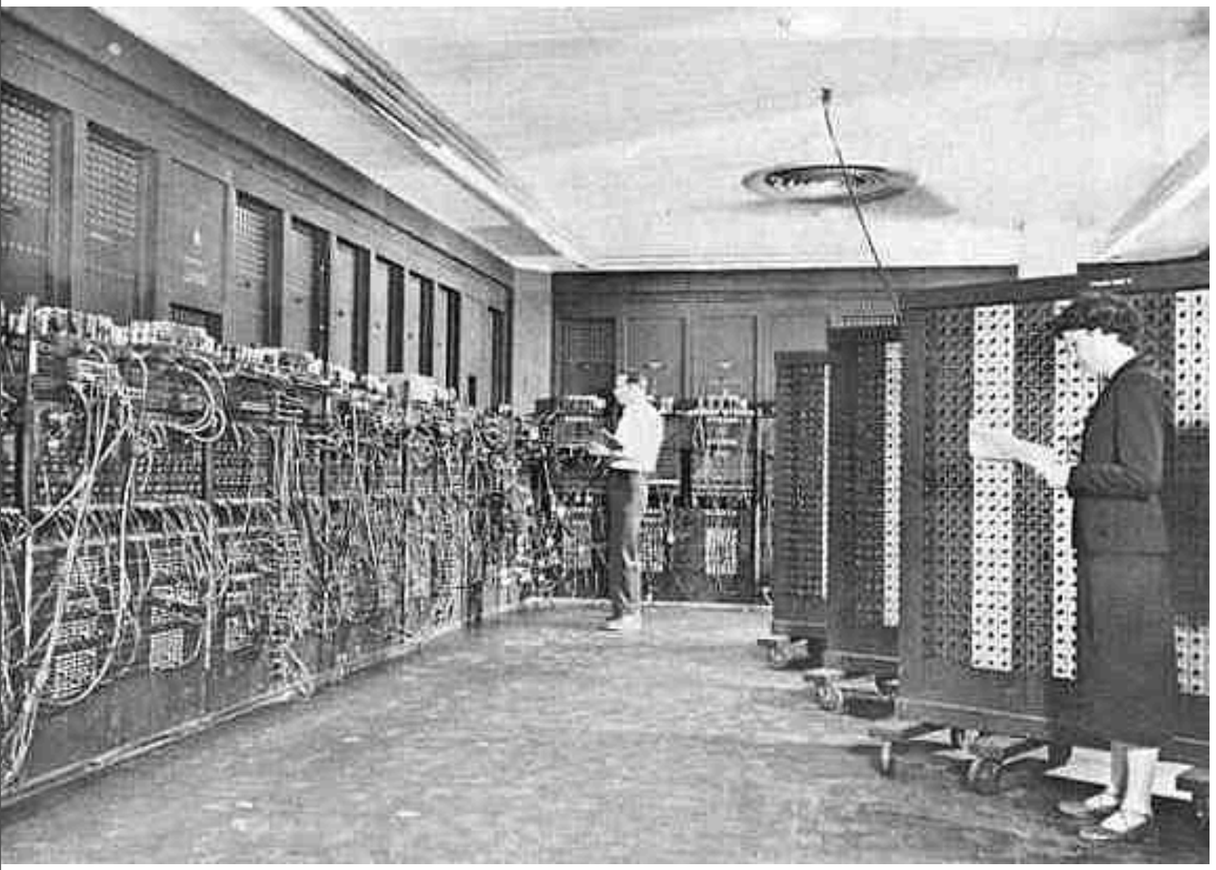
Astrolabe (since 200BC)



1673 - Leibniz

“Turing machines”

“Turing machines”

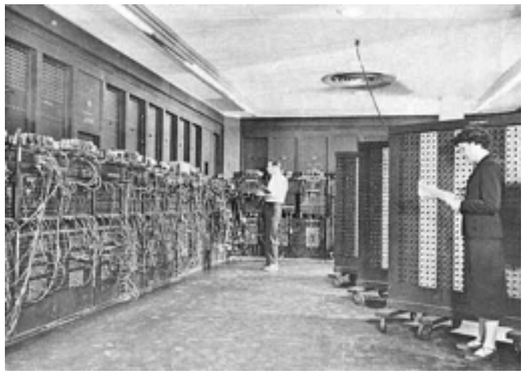


1946 - ENIAC

2007 - Blue Gene

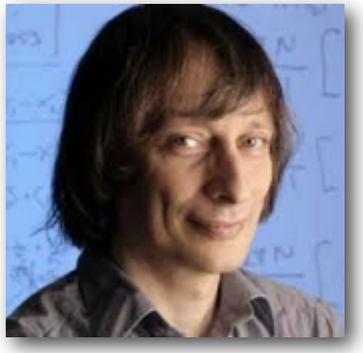
Non-universal

Universal



Classical

Quantum



"*Quantum* Turing machines"

Classical

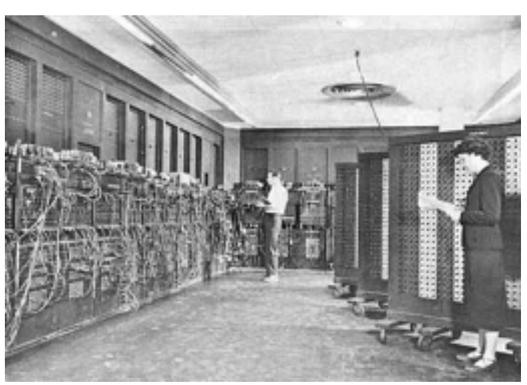
Quantum

Non-universal

Non-universal

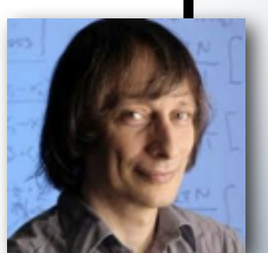
Universal

Universal



Classical

Quantum



Universal
Quantum
Computers

Quantum Annealers

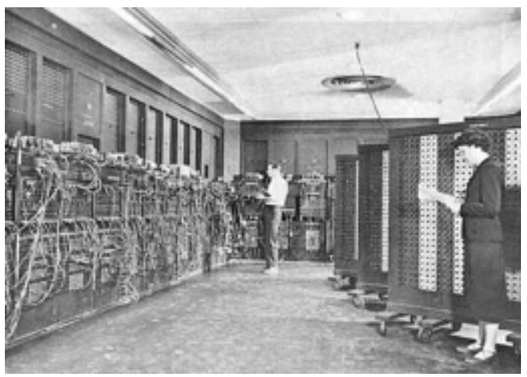
Classical | Quantum

Non-universal

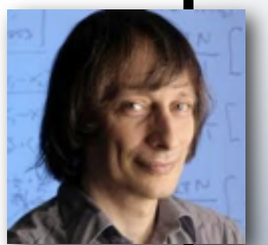
Non-universal

Universal

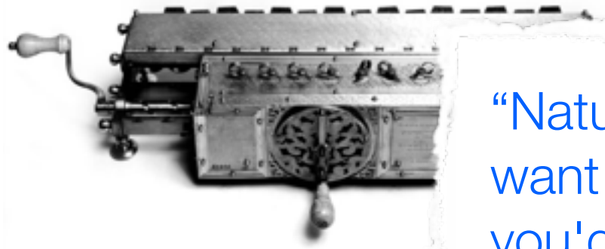
Universal



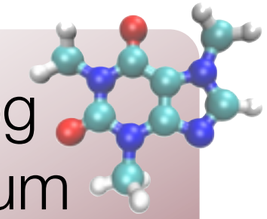
Classical | Quantum



Universal Quantum Computers



Quantum

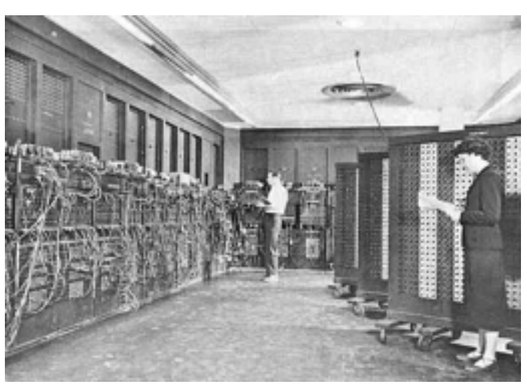


Analog
Quantum
Simulators

"Nature isn't classical, dammit, and if want to make a simulation of nature, you'd better make it quantum mechanical, and by golly it's a wonderful problem because it doesn't look so easy."

Non-universal

Universal

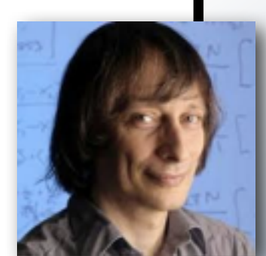


Classical

Quantum

Non-universal

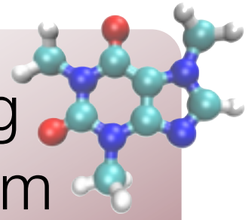
Universal



Universal
Quantum
Computers

Quantum Annealers

Analog Quantum Simulators



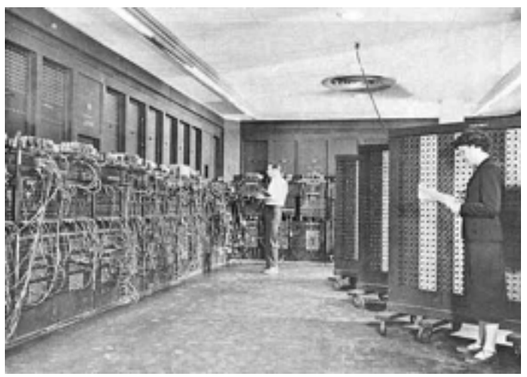
Classical | Quantum

Non-universal

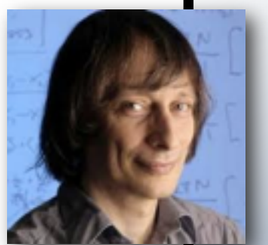
Non-universal

Universal

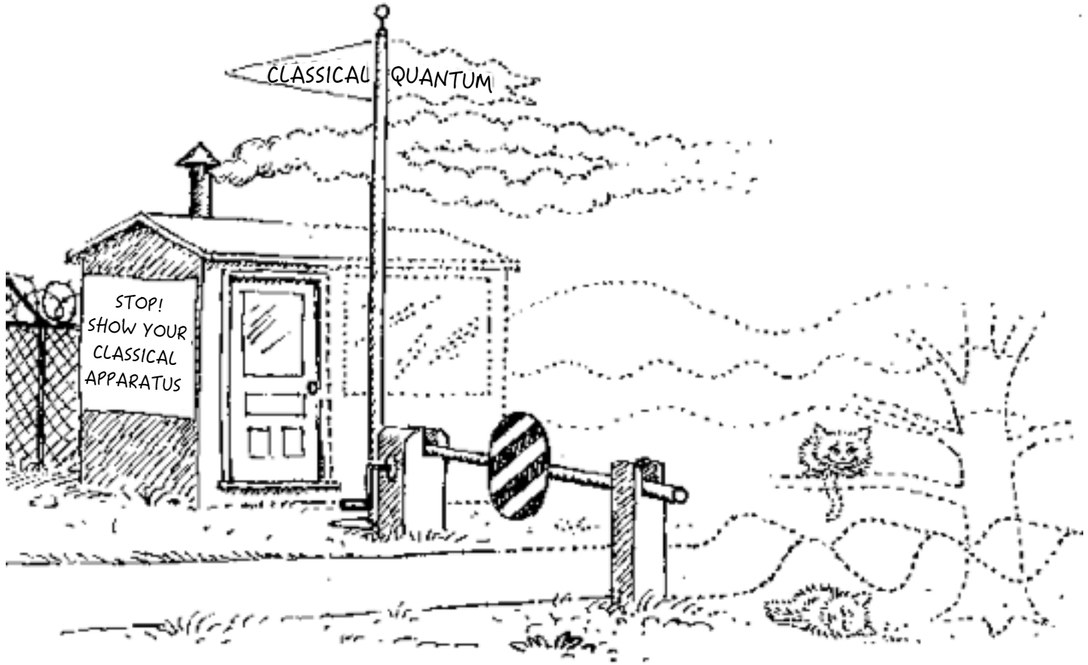
Universal



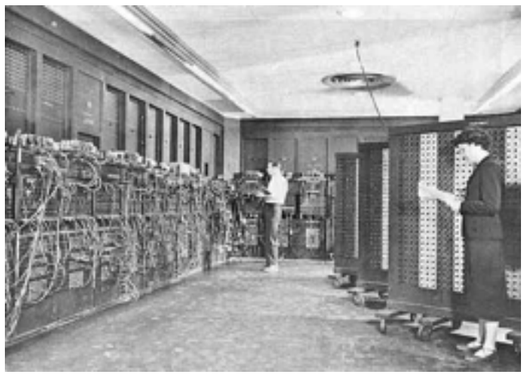
Classical | Quantum



Universal Quantum Computers



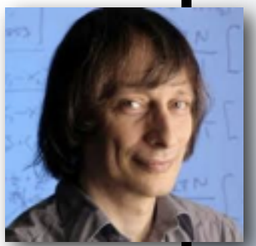
Universal



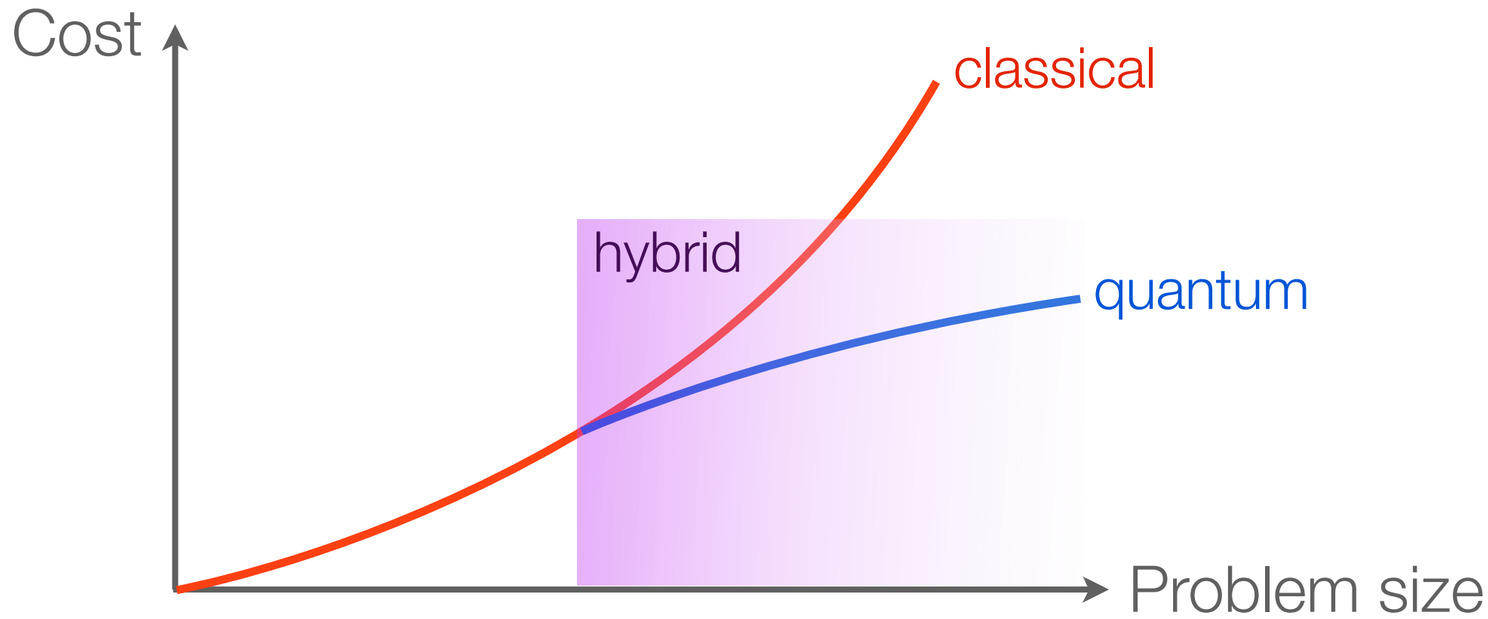
Classical

Quantum

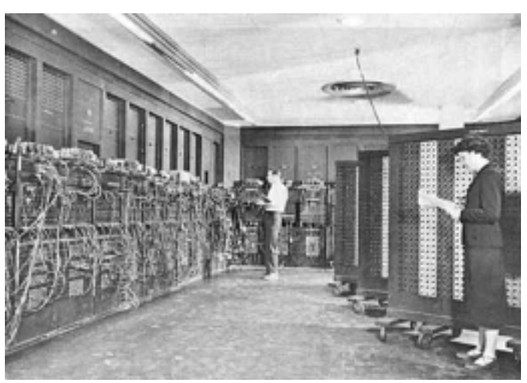
Universal



Universal
Quantum
Computers



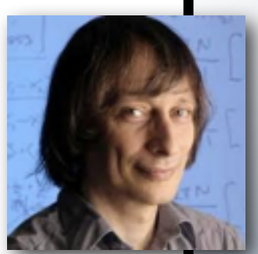
Universal



Classical

Quantum

Universal

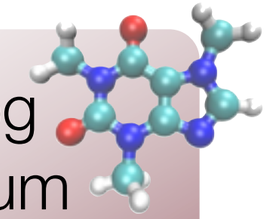


Universal
Quantum
Computers

Applications

Quantum Annealers

Analog Quantum Simulators

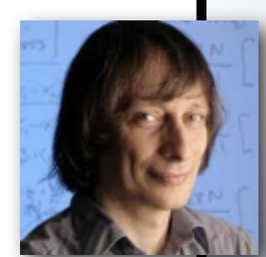


Quantum

Non-universal

Universal

Quantum



Universal Quantum Computers

Chemistry
e.g. catalyst design

Big data

Security
e.g. secure communication and computing

Optimisation
e.g. cognitive computing & business processes

Machine learning

Materials Science
e.g. energy-efficient devices

Measurement

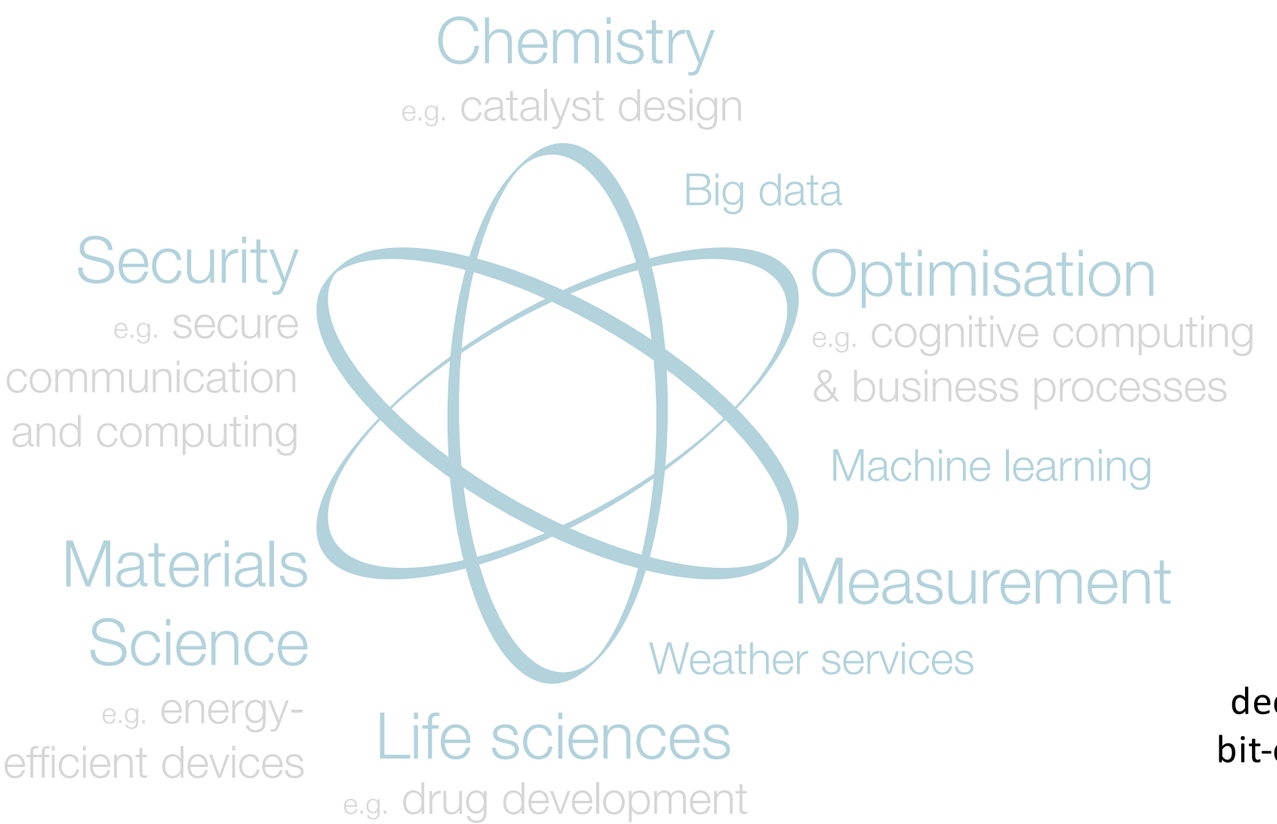
Weather services

Life sciences
e.g. drug development

See also: “Quantum Algorithm Zoo”
http://math.nist.gov/quantum/zoo/

Case study: Error correction decoding

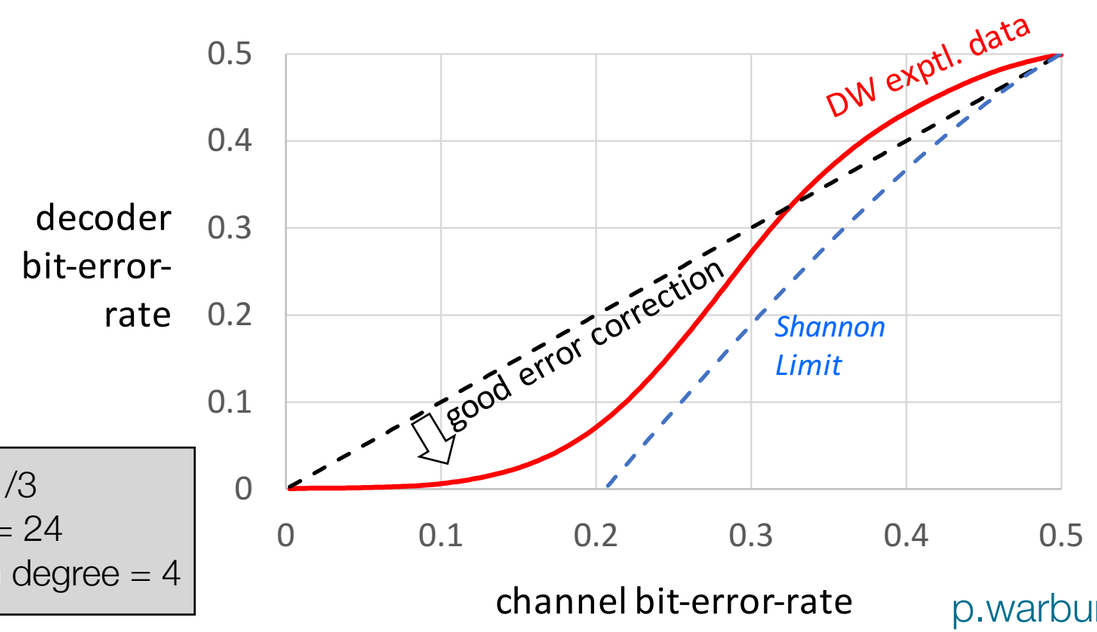
Quantum Annealers



Ising code

- Introduced in 1989 (Sourlas, Nature 339 693)
- Similar to low-density parity check (LDPC) codes
- Saturates Shannon's bound for high degree of coding graph

Decoding is NP-complete (like LDPC)
Possible solution: decode by **quantum annealing**



main limitation of current hardware →

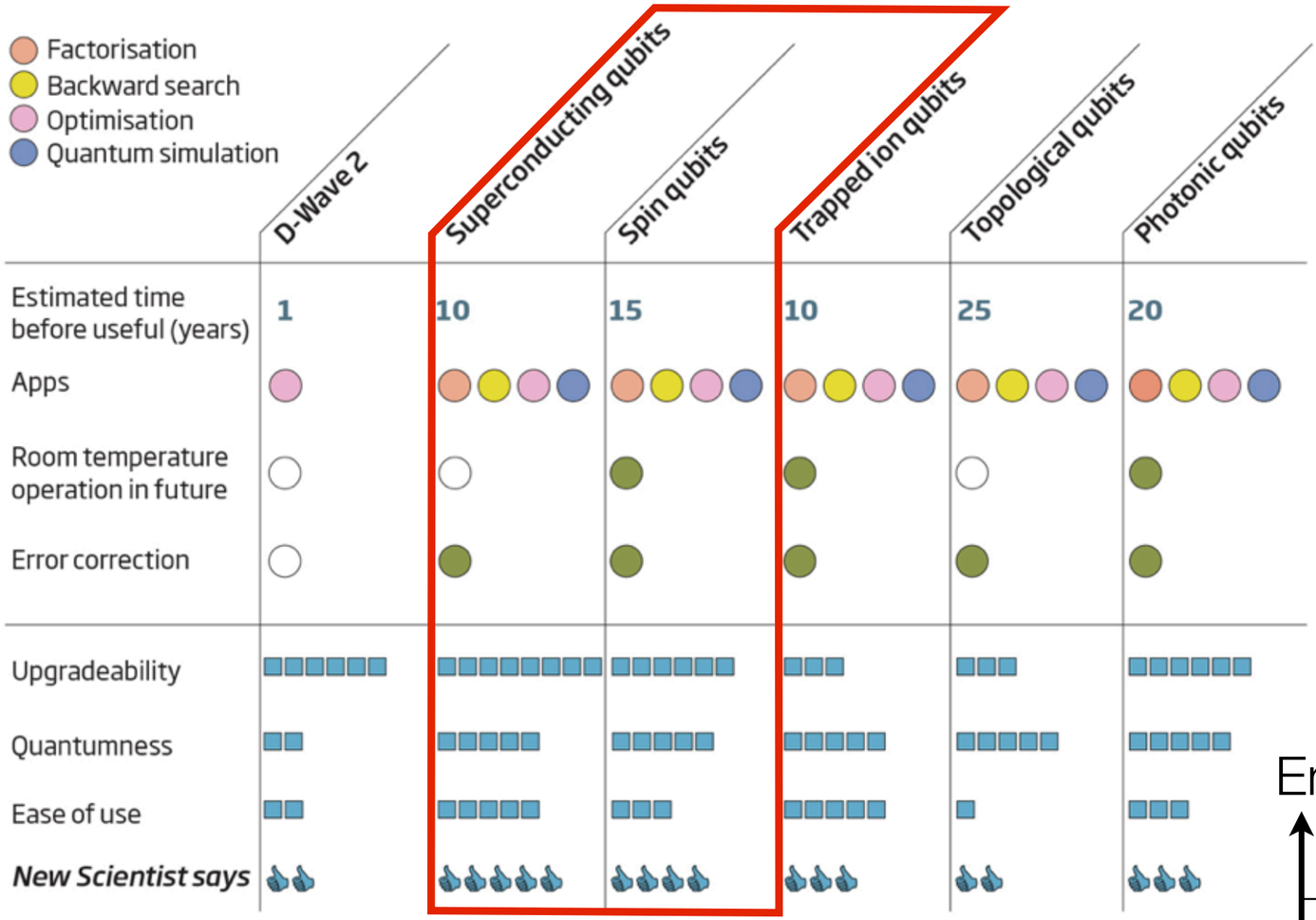
Code rate = 1/3
Block length = 24
Coding graph degree = 4

p.warburton@ucl.ac.uk

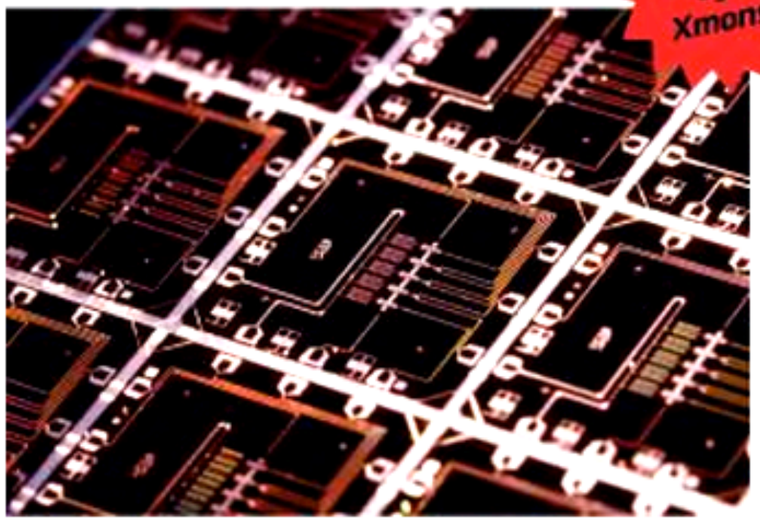
2.
How to build a universal quantum computer
?

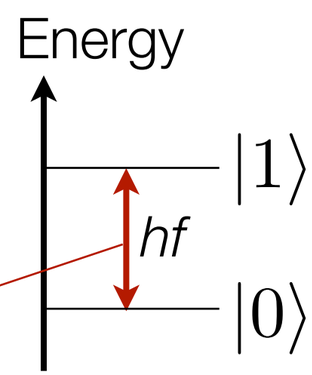
Which quantum computer is right for you?

There are many types to choose from. Here's how they compare and our all-important verdict



Spin or superconductor? It's the "Apple vs Android" of the quantum computing world. Here's what you need to know to choose





control & readout

in microwave domain
4 - 40 GHz

Hybrid spin/ superconductor

www.newscientist.com/special/quantum-buyers-guide

Qubit requirements

Quantum coherence lifetime

- Timescale for quantum information to evolve into a classical information

High fidelity operations > 99.9%

- State preparation
- Control
- Readout

Universal gates and fault tolerant architecture

- Qubit coupling capable of performing universal logic gates and error correction

Scalability

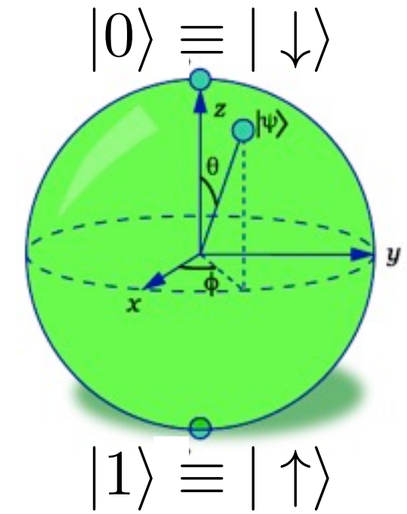
- Achieving a useful number of logical qubits may require large numbers $>10^6$ of physical qubits

Spin qubits

CMOS compatibility

Silicon and diamond leading platforms

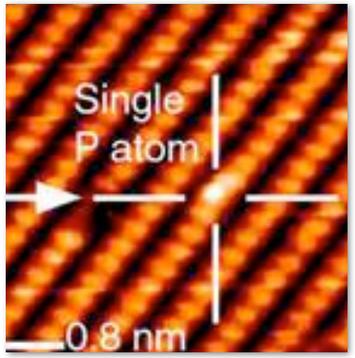
Entanglement using light

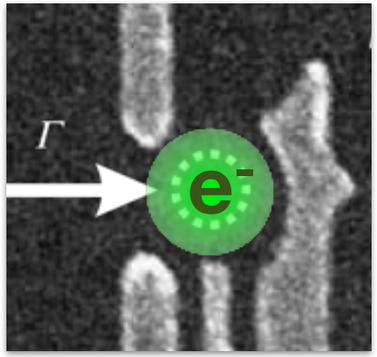


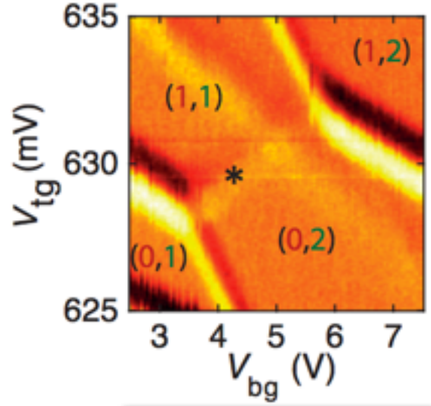
Long quantum coherence lifetimes: 3 seconds (electron spin in Si)
3 hours (nuclear spins in Si)

High fidelity operations $\mathscr{F}$ ~99.9% for quantum logic gates
$\mathscr{F}$ ~97 - 99.8% for measurement (e-/n-spin)

Atomic dopants and quantum dots ('artificial atoms')

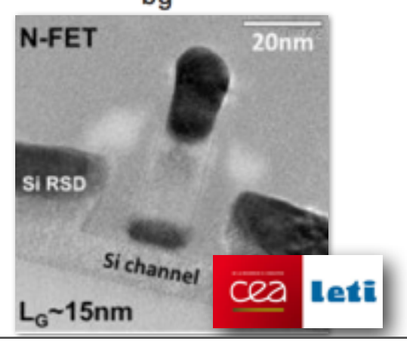


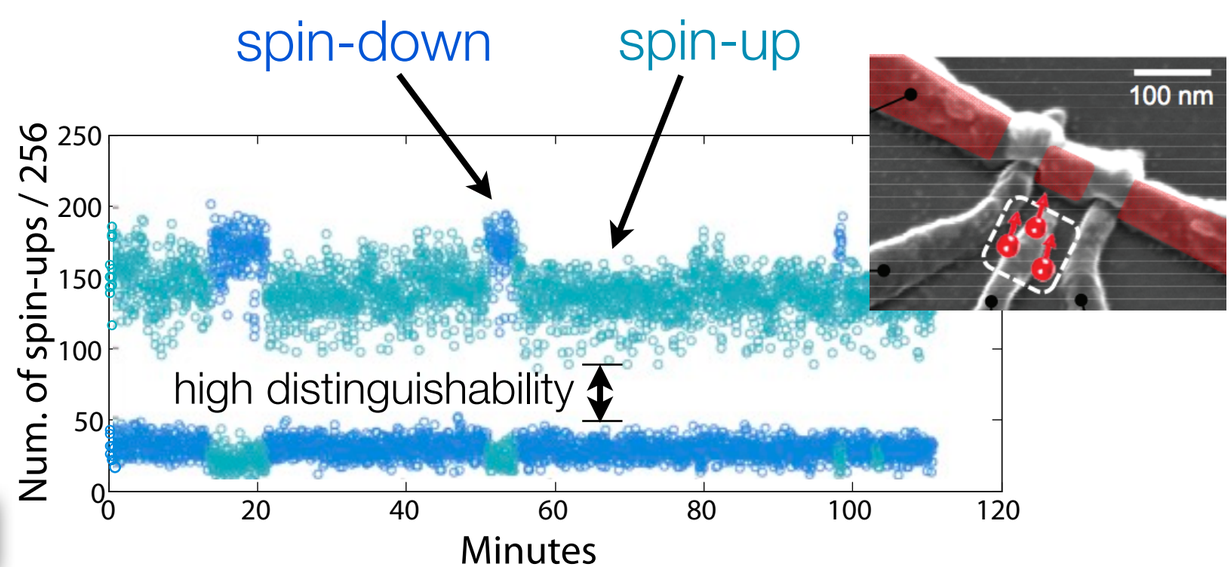




...
or both

Currently still at the 1-2 qubit level





Urdampilleta *et al.*, Phys Rev X **5** 031024 (2015)

Elzerman *et al.*, Nature **430** 431 (2004)

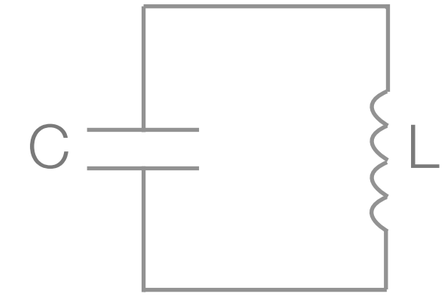
Muhonen *et al.*, J Phys Cond Mat **27** 154205 (2015)

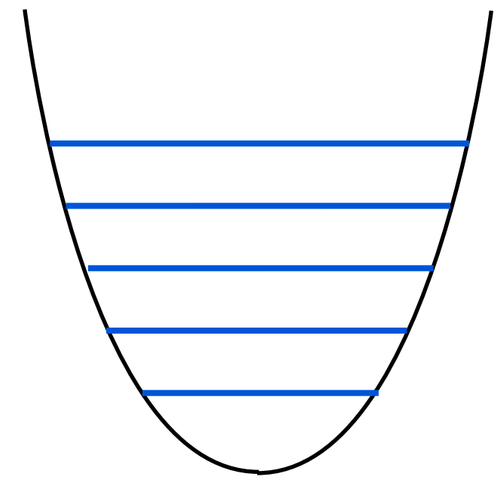
Pla *et al.*, Nature **489** 541 (2012); Nature **496** 334 (2013)

Saeedi *et al.*, Science **342** 830 (2013)

Wolfowicz *et al.*, Nature Nano **8** 561 (2013)

Superconducting qubits



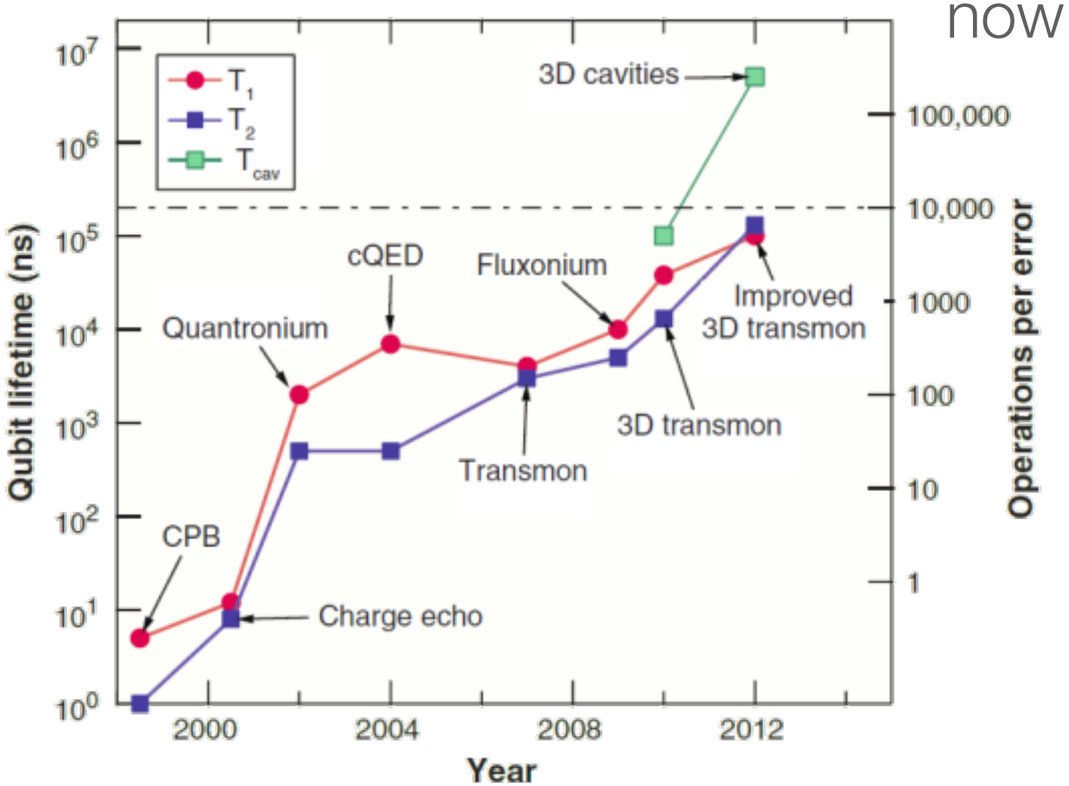


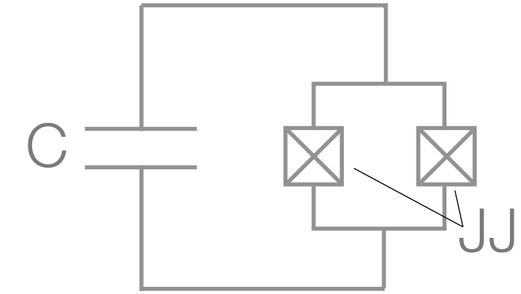
harmonic

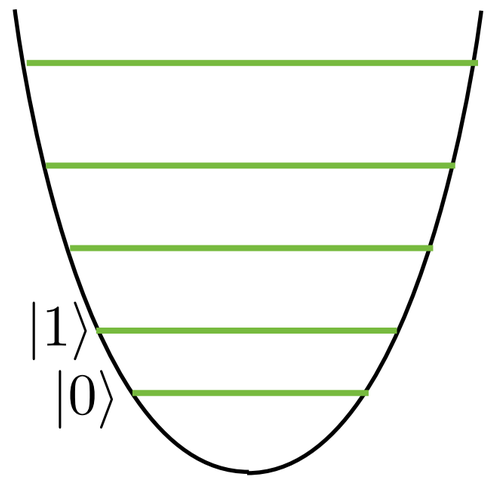
Superconducting qubits

Mostly based around Al Josephson junctions

Quantum coherence lifetimes have improved dramatically in 10 yrs
now many 10s of microseconds



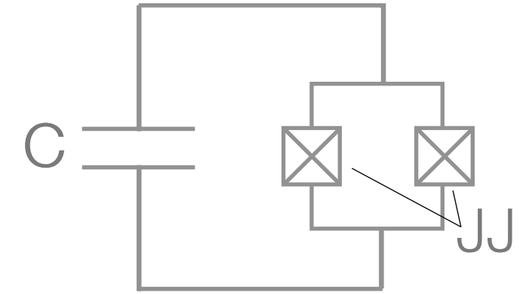




anharmonic

Devoret & Schoelkopf, Science **339** 1169 (2013)

Superconducting qubits



Mostly based around Al Josephson junctions

Quantum coherence lifetimes have improved dramatically in 10 yrs
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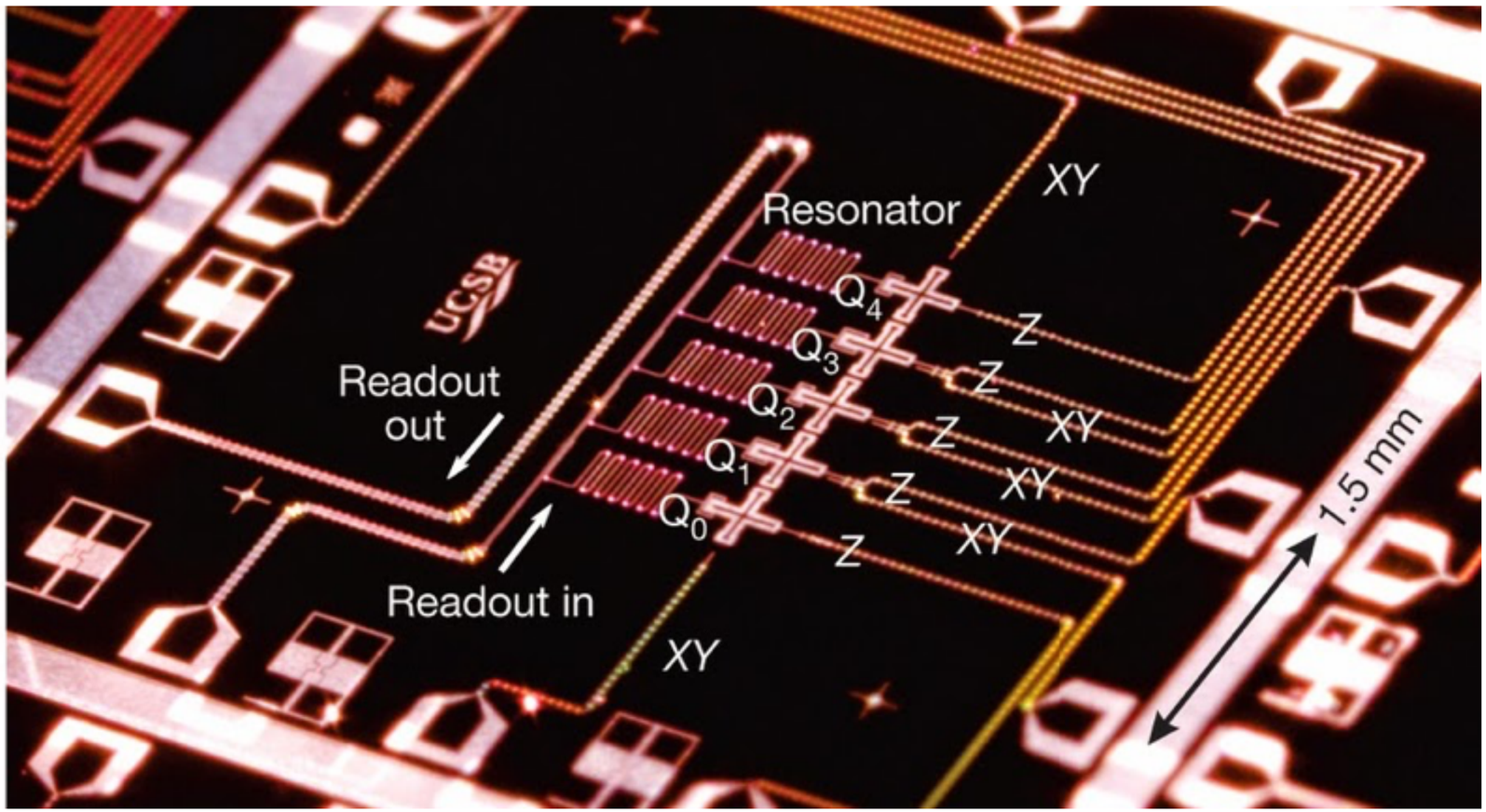


High fidelity operations

$\mathscr{F}$ ~99.9% for single-qubit gates

$\mathscr{F}$ ~99.4% for two-qubit gates

$\mathscr{F}$ ~99% for measurement

Google IBM

Currently at ~10 qubits

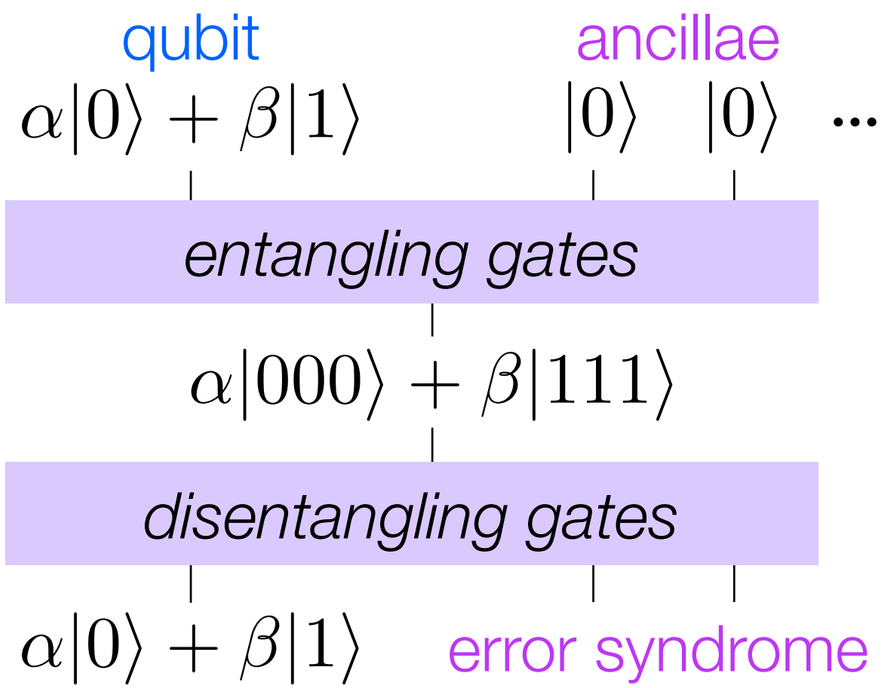
Bahrends *et al.*, Nature **508** 500 (2014)

Devoret & Schoelkopf, Science **339** 1169 (2013)

Error correction

Protection through redundancy

(e.g. classical three bit repetition code)



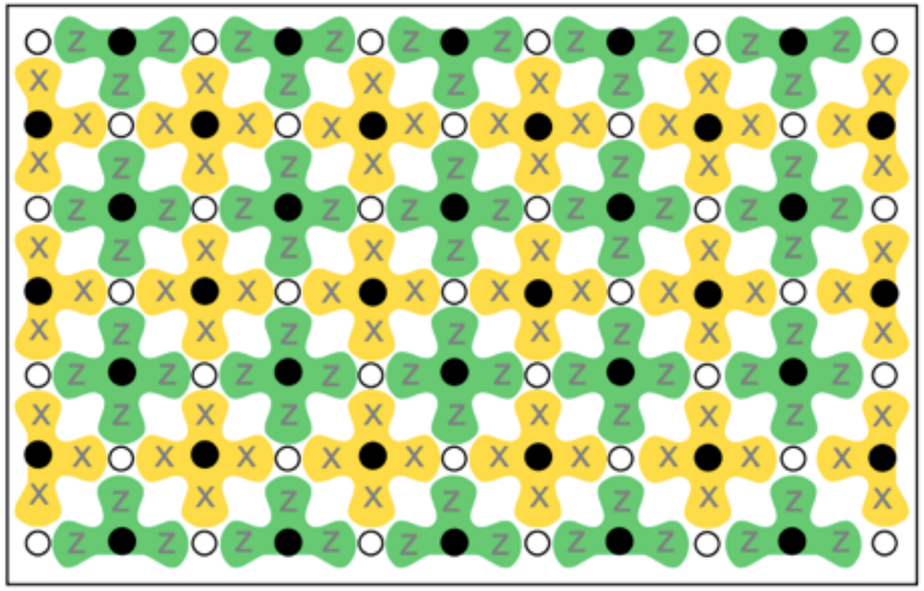
N physical qubits for 1 logical qubit

Errors must be below some critical rate to ensure fault tolerance

Early codes required $\mathscr{F}$ > 99.99 - 99.999%

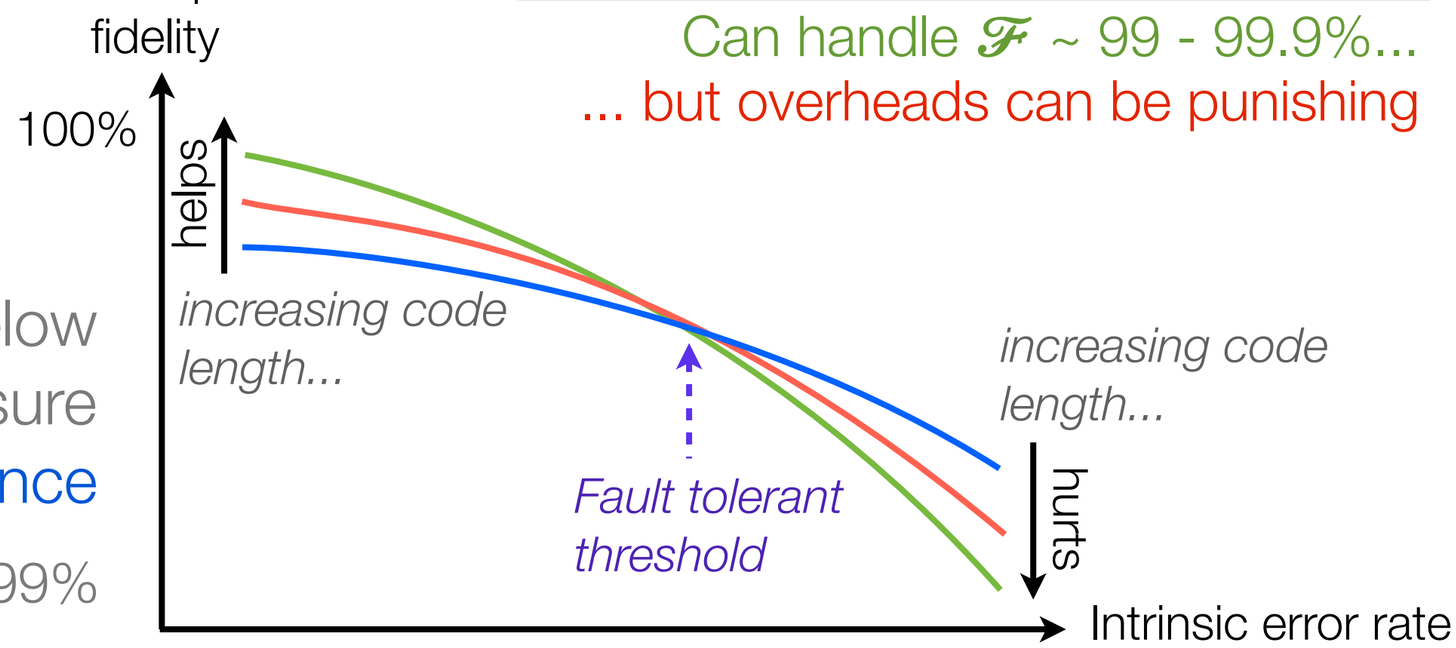
Surface code

- Parity measurements stablise qubits



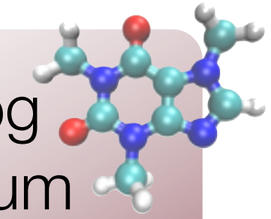
Can handle $\mathscr{F}$ ~ 99 - 99.9%...

... but overheads can be punishing



Progress towards universal quantum computers can also improve non-universal quantum computing devices

Quantum Annealers



Analog Quantum Simulators

Chemistry
e.g. catalyst design

Big data

Security
e.g. secure communication and computing

Optimisation
e.g. cognitive computing & business processes

Machine learning

Materials Science
e.g. energy-efficient devices

Measurement

Weather services

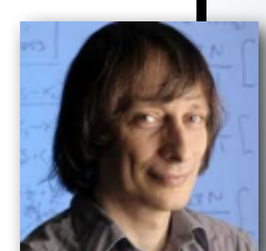
Life sciences
e.g. drug development

Non-universal

Universal

Better control

Better qubits



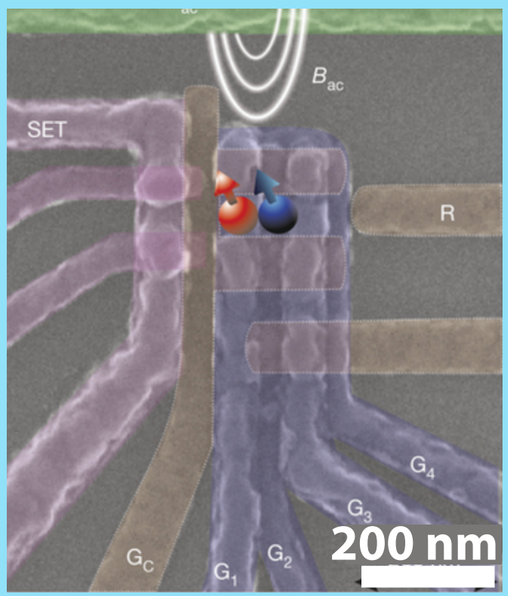
Universal Quantum Computers

Coupling architectures

Inter-qubit separation

Characteristic length of 10^8 physical qubit 2D array

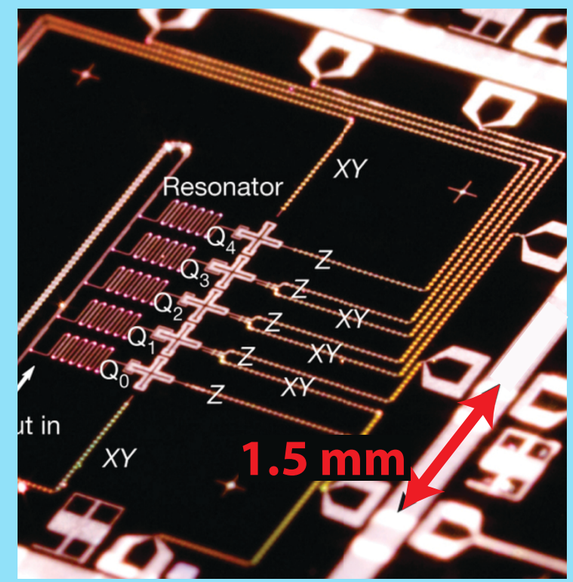
10 - 100 nm
0.1 - 1 mm



e.g. Exchange-coupled quantum dots, dopant spins

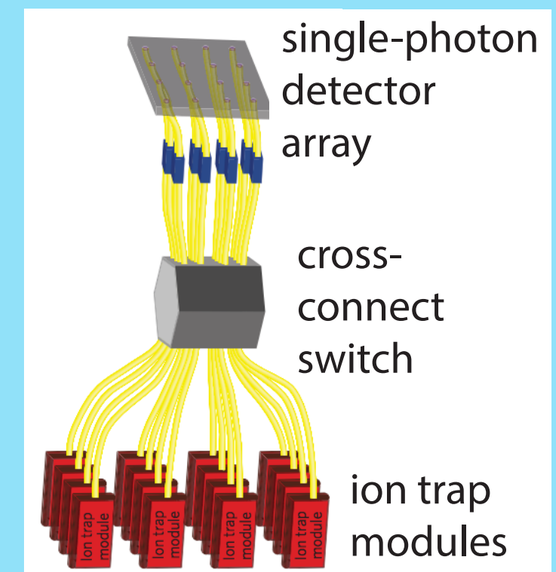
1 - 10 μm
1 - 10 cm

0.1 - 1 mm
1 - 10 m



e.g. Transmon super-conducting qubits or spin qubits, coupled to microwave resonators

1 - 10 cm
30 - 300 m



e.g. Ion-traps, quantum dots, or NV-centres in diamond, entangled by coupling to optical photons

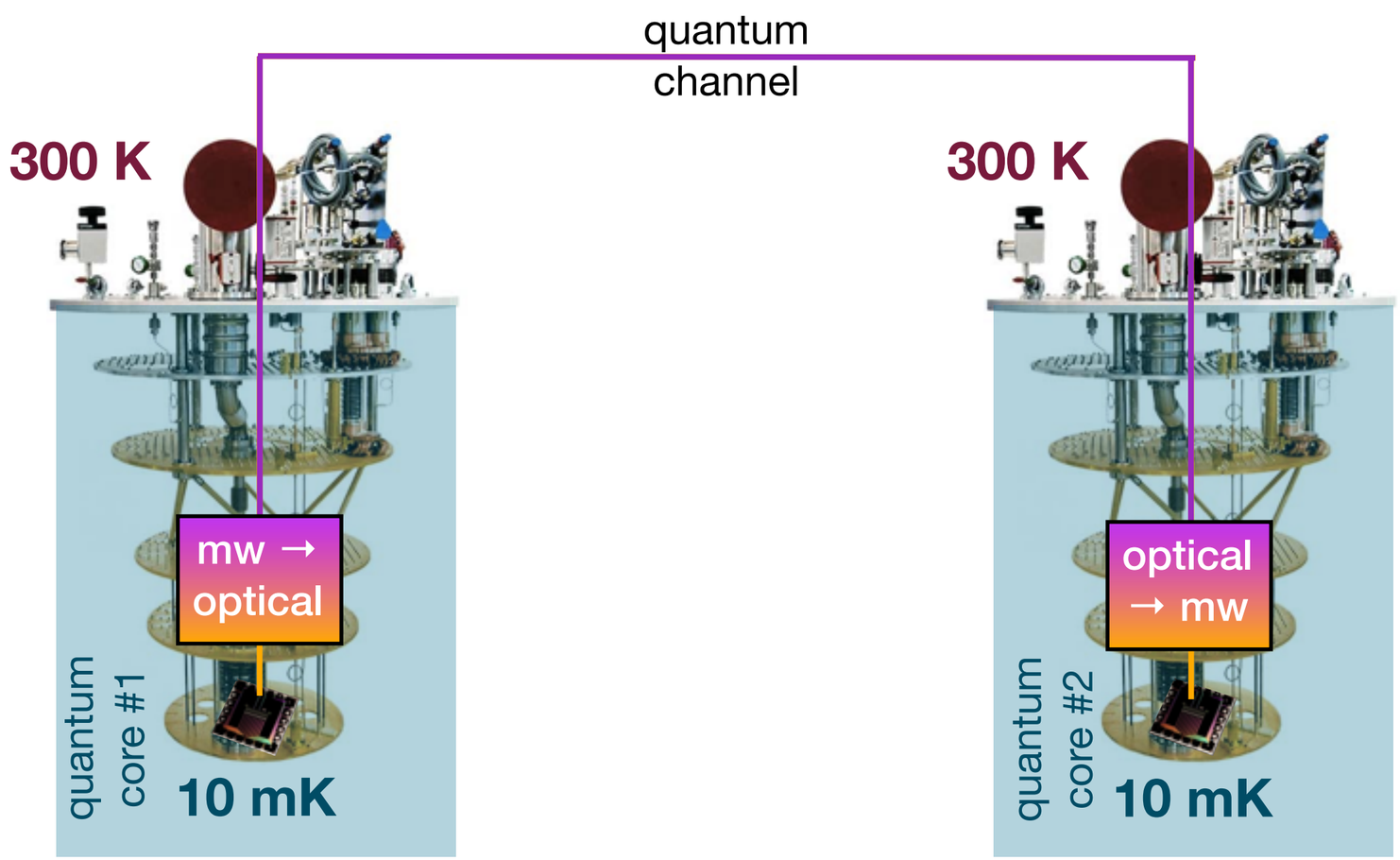
Ease of addressability

Qubit density

Thinking outside the box

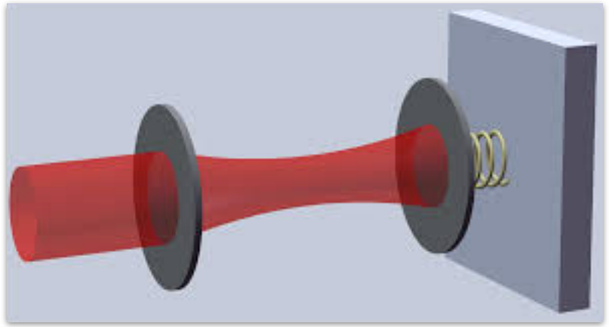
Thinking outside the box

Microwave - optical quantum frequency conversion

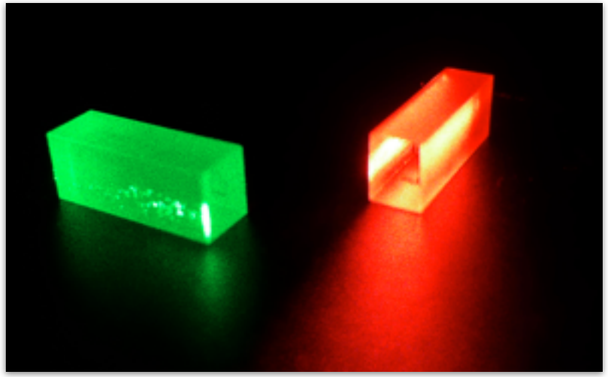


Implementations

Opto-mechanics

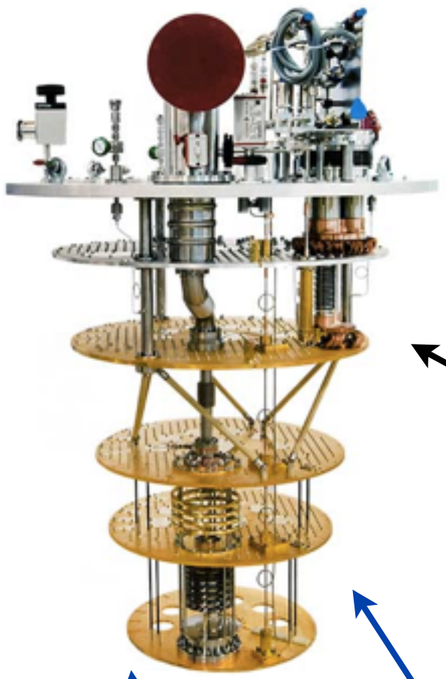


Rare earth-doped crystals



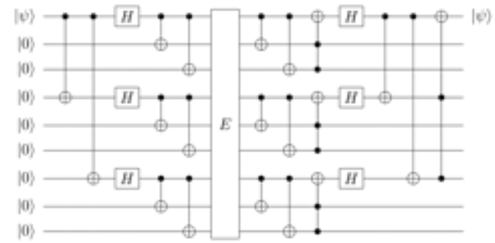
Quantum Engineering

Cryogenics

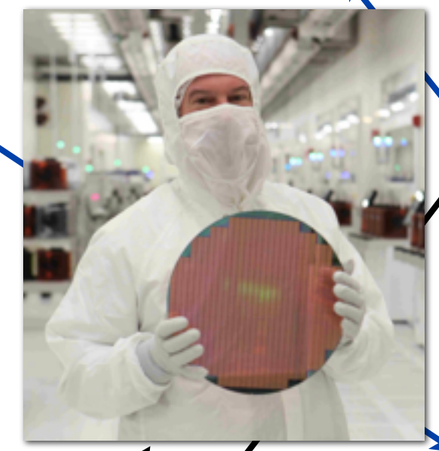


Quantum interfaces
e.g. to quantum comm

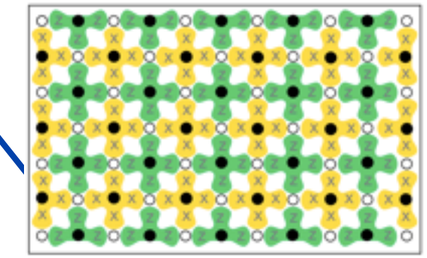
Quantum algorithms
software engineering



Fabrication



Quantum architectures

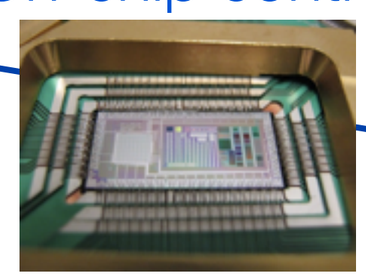


System modelling

Quantum processor

Control electronics
R.T. and cryo

On-chip control



System characterisation
Monitoring & calibration

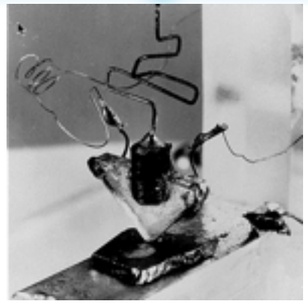
Control software
inc. error correction

Microwave engineering

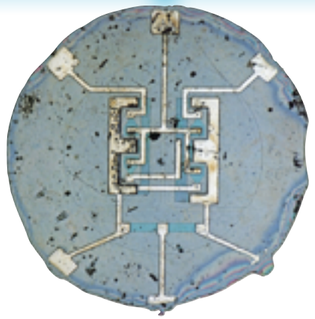
The “when” question...

Quantum mechanics & FET patent
1920s

Transistor
1947



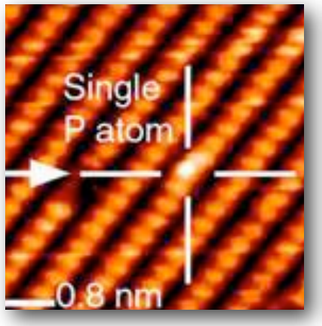
Integrated circuit
1958

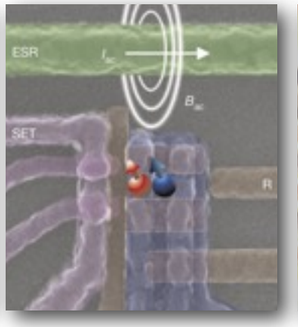


First microprocessor sold
1971

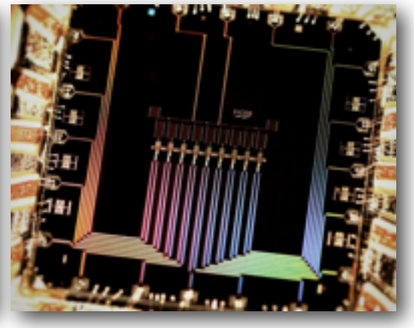
Quantum computers proposed
1980s

Single qubits
2000-2012





Quantum integrated circuit
2018?



First Q processor sold
2031?

...?

More

UCLQ Quantum Science & Technology Institute

www.uclq.org

Research, training and innovation in quantum technologies

QUEST2

Quantum Engineering with Solid-State Technologies

Capital equipment for fabrication and cryogenic test & measurement

Quantum spin dynamics

www.ucl.ac.uk/qsd

Research group targeting spin-based quantum technologies

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

uknqt.epsrc.ac.uk

National programme to accelerate development of quantum technology

Questions?

Q&I

www.qandi.co.uk

Consultancy covering full range of quantum technologies