Quantum Computing:
A new era in information technology

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Quantum Computing is *Different*

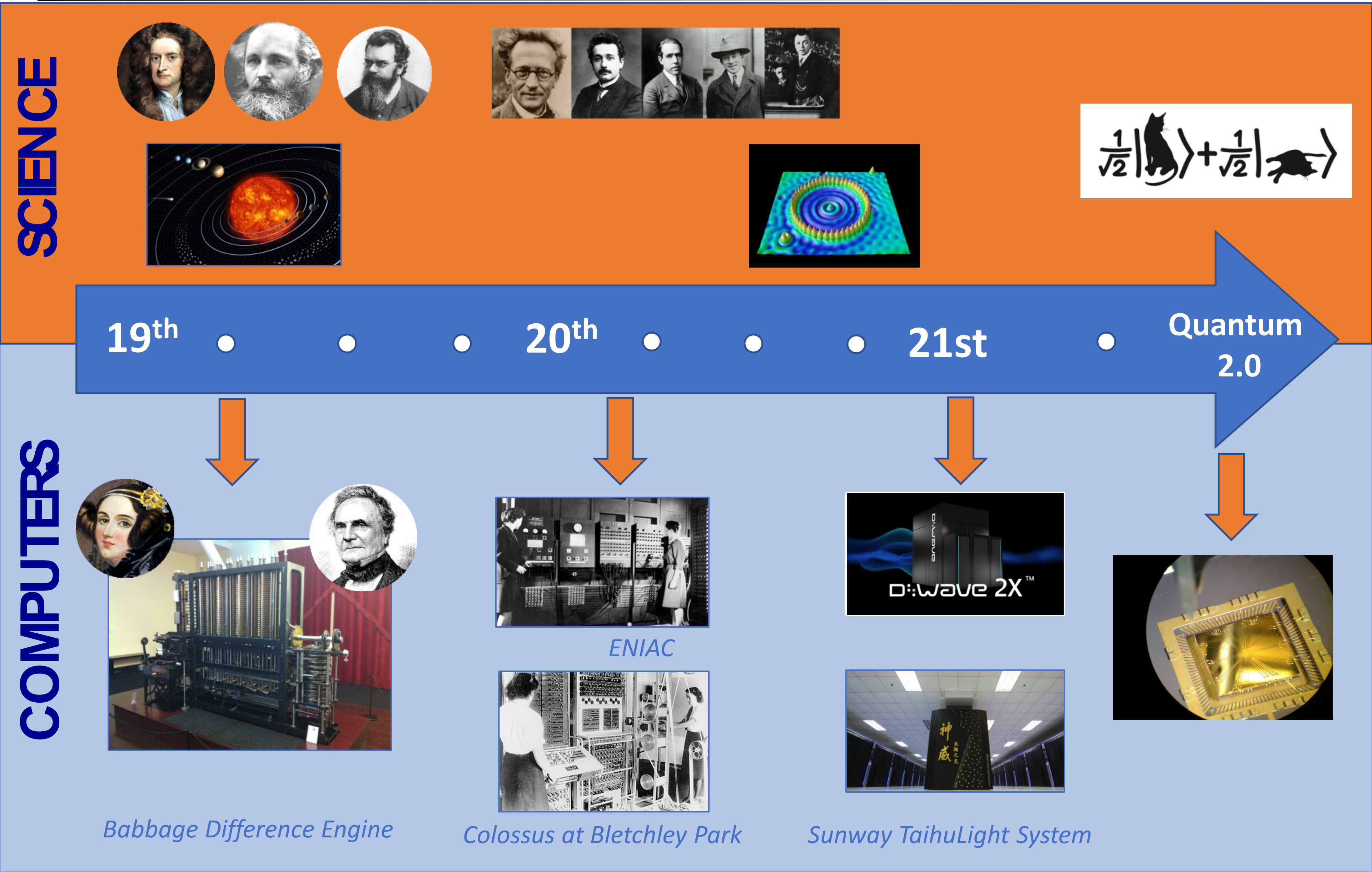
"Quantum information is a radical departure in information technology, more fundamentally different from current technology than the digital computer is from the abacus."

W. D. Phillips
Nobel laureate 1997

Saunpan Abacus

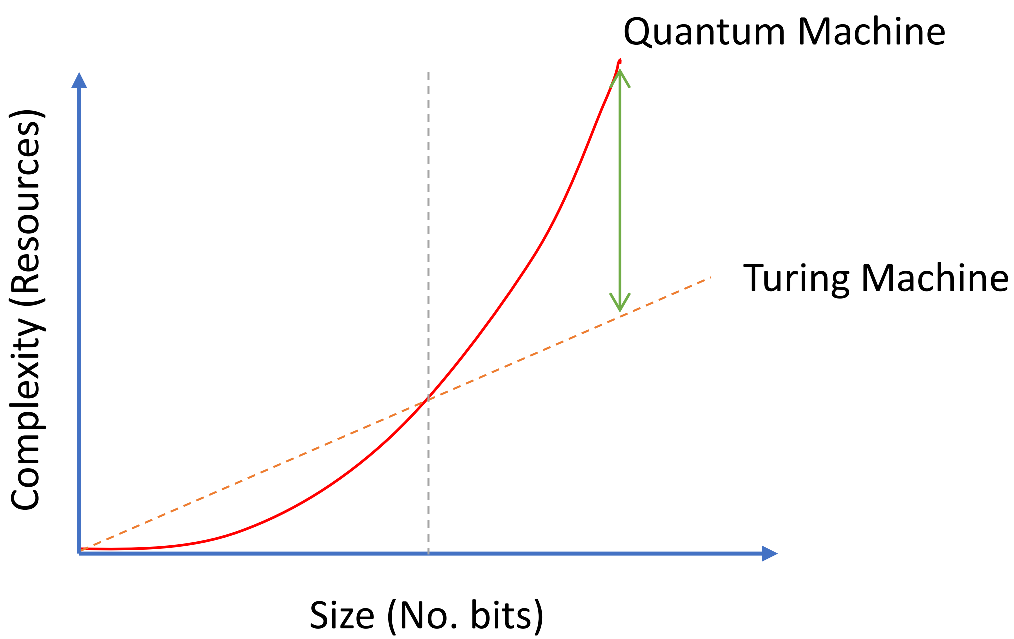
Modern Laptop Computer

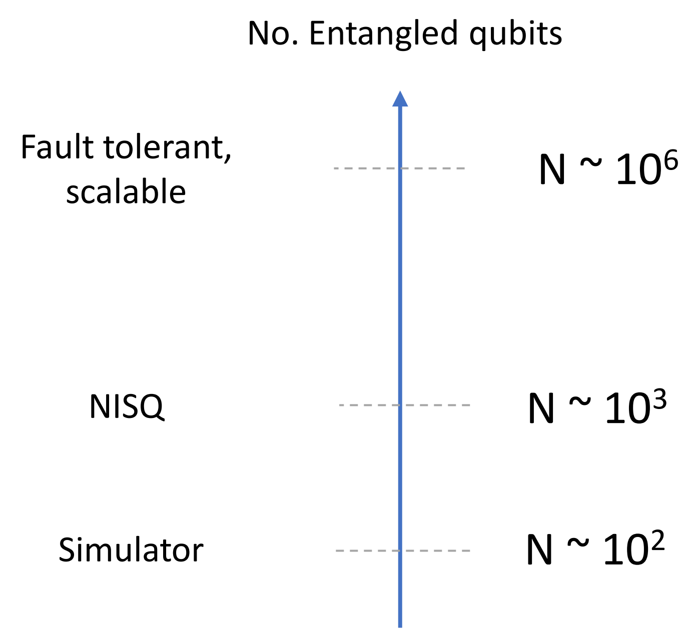
Science & Computation: a recent history



Complexity and Scaling

Certain problems are ”hard” for Turing Machines – and ”easy” for Quantum Machines

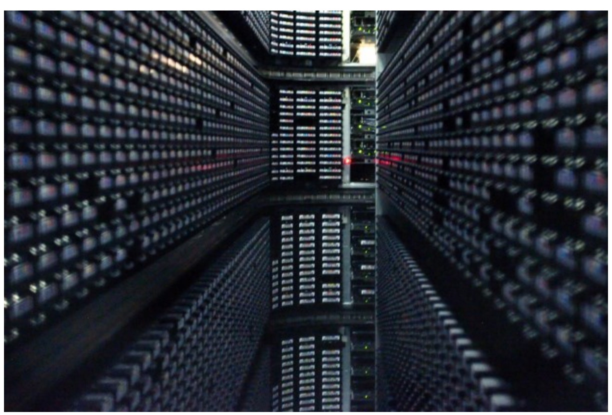




Anticipated applications

Data encryption

Drug discovery

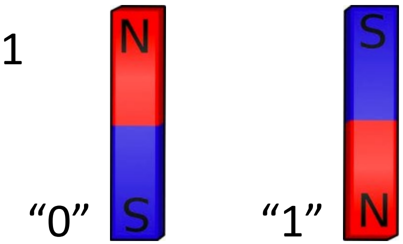


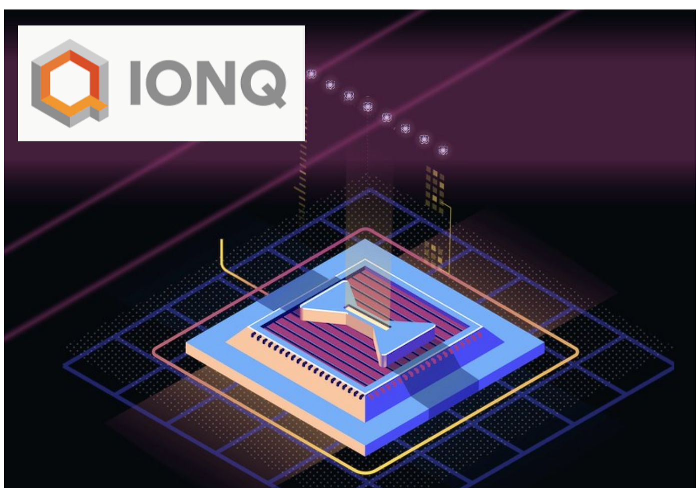
Big Data

Logistics

Quantum Computing is *Different*

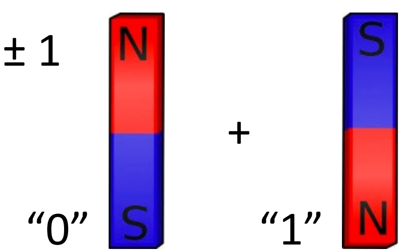
Bit: 0 or 1





Superposition:

QuBit: 0 ± 1



Superposition

Classical Physics:
A switch is OFF (0)
or ON (1)

0 or 1, binary, is the basis for classical computing – the “bit”

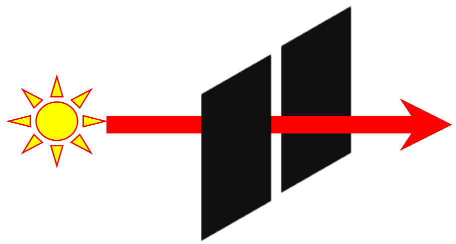
Quantum Physics:
A switch may be OFF
and ON

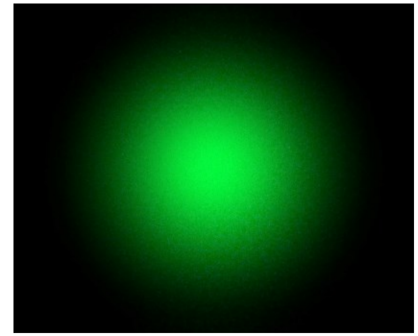
0 and 1 is called a ‘superposition’ and the basis for quantum computing is the “qubit”

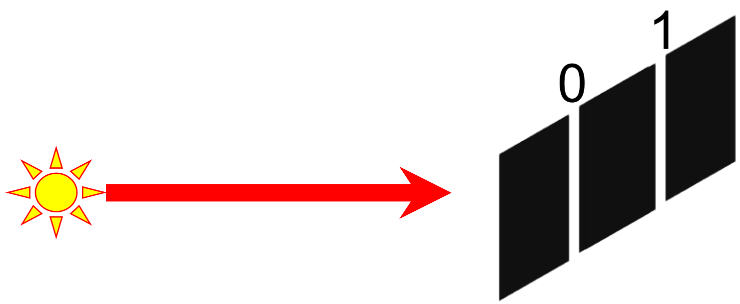
Quantum physics tells us there are more possibilities

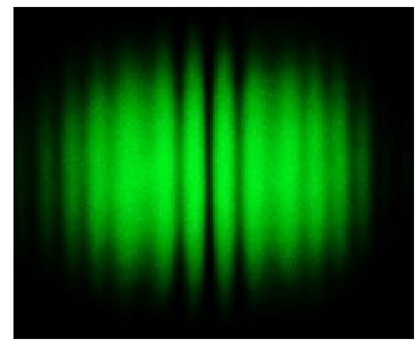
Illustrating superposition with light

A ‘photon’ is a particle of light

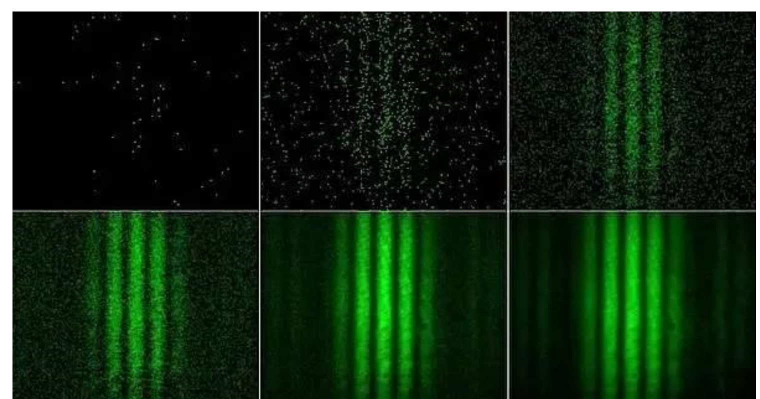








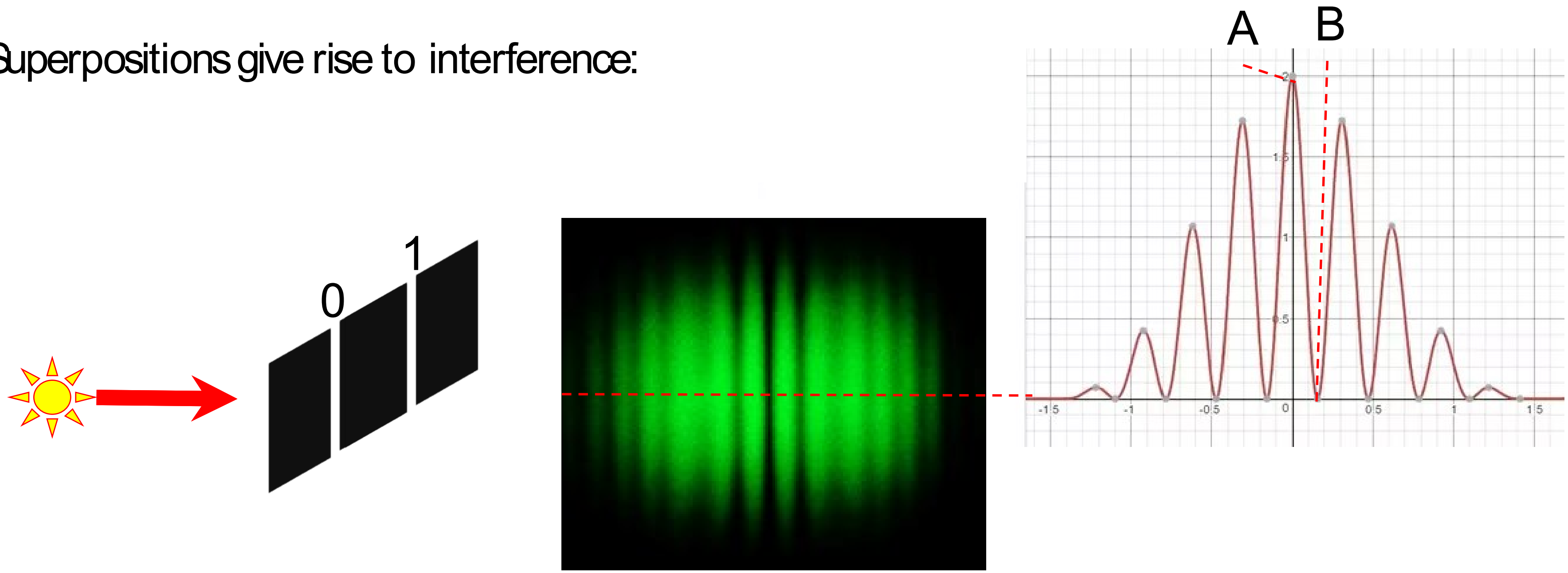
Quantum physics says that even a single photon can pass through both slits



A single photon encodes a “qubit” – a **superposition** of “0” + “1”

Superposition and interference

Superpositions give rise to interference:



Probability of photon arriving at A or B through slit 0 = a^2

Probability of photon arriving at A or B through slit 1 = b^2

Probability of photon arriving at A through both slits = $(a+b)^2 \sim 1$ (constructive)

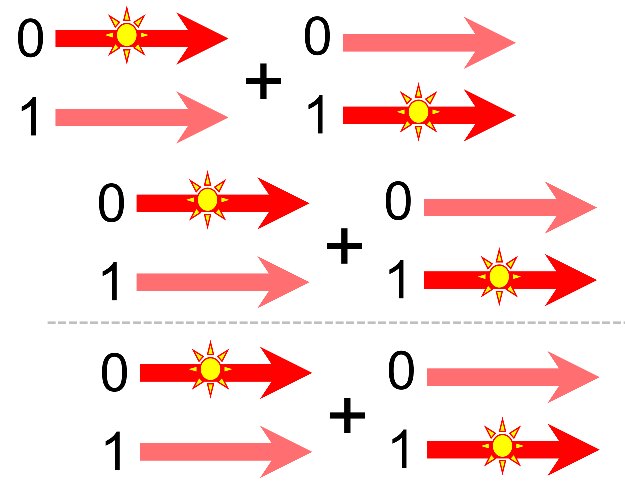
Probability of photon arriving at B through both slits = $(a-b)^2 \sim 0$ (destructive)

Quantum algorithms are protocols that arrange for constructive interference around the answer

Entanglement: the quantum difference

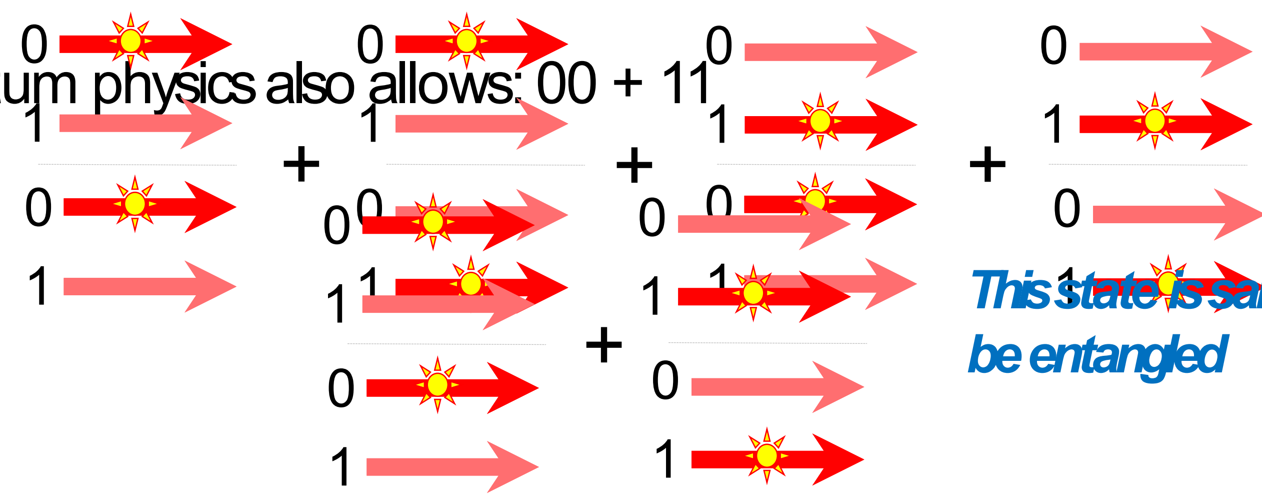
One qubit can be in state 0+1.

Two qubits can be in state (0+1) (0+1).



We can think of this as: 00 + 01 + 10 + 11.

But quantum physics also allows: 00 + 11

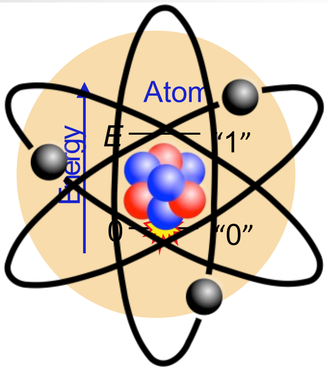


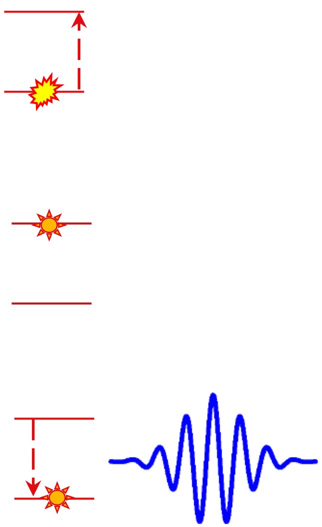
This state is said to be entangled

Quantum in matter

Light is useful for moving information around.

Atoms are good for storing and processing it.



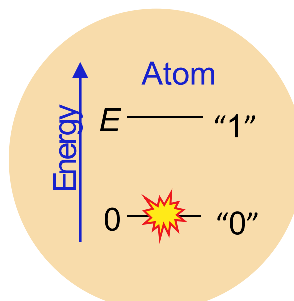


Atoms as qubits

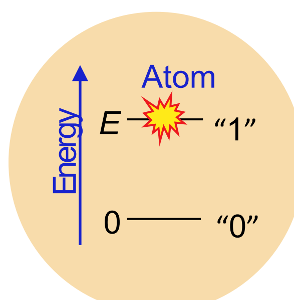
The atom can be in a superposition of its ground and excited states.

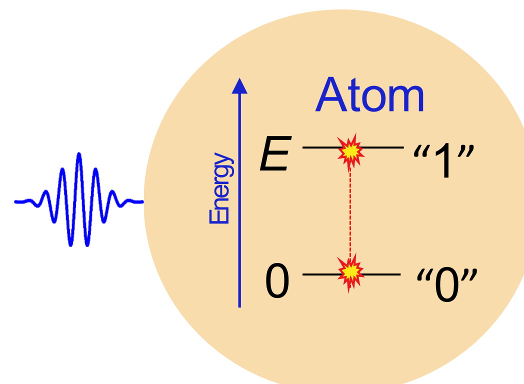
These states can be used to encode a qubit.

Atom in logical state “0”



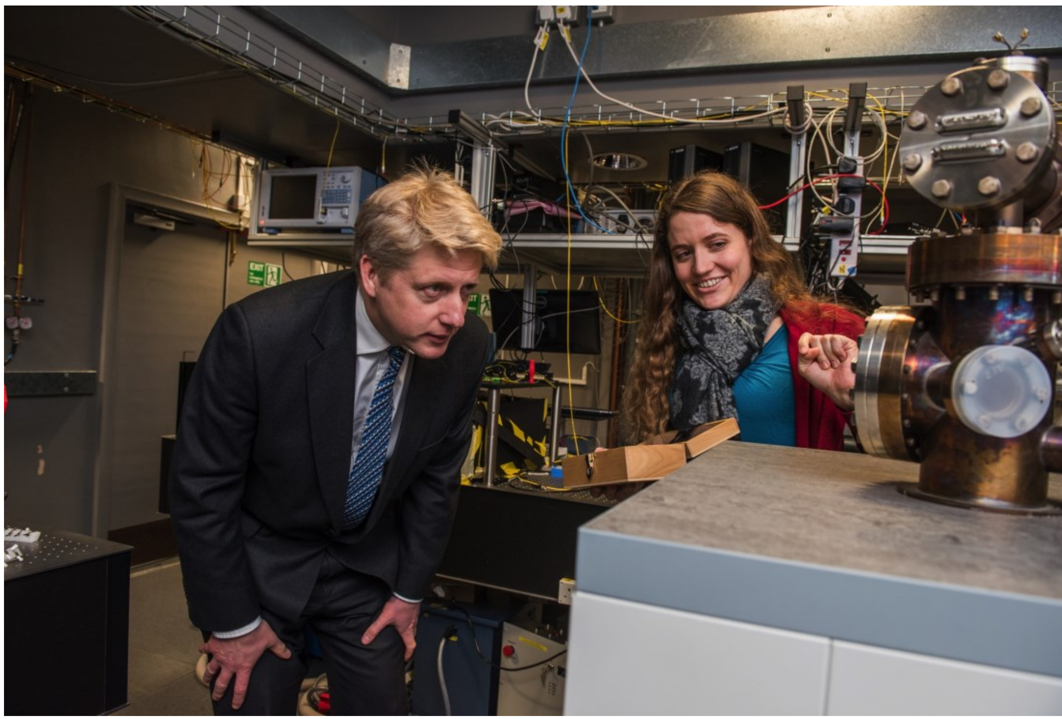
Atom in logical state “1”

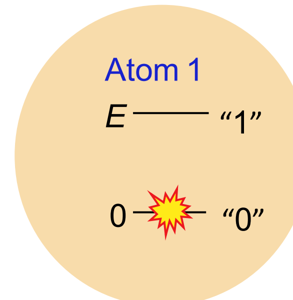




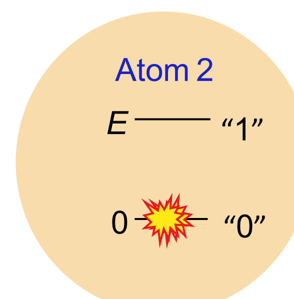
Atom in superposition state “1+0”

Entangling atoms using light: Gate Fidelity



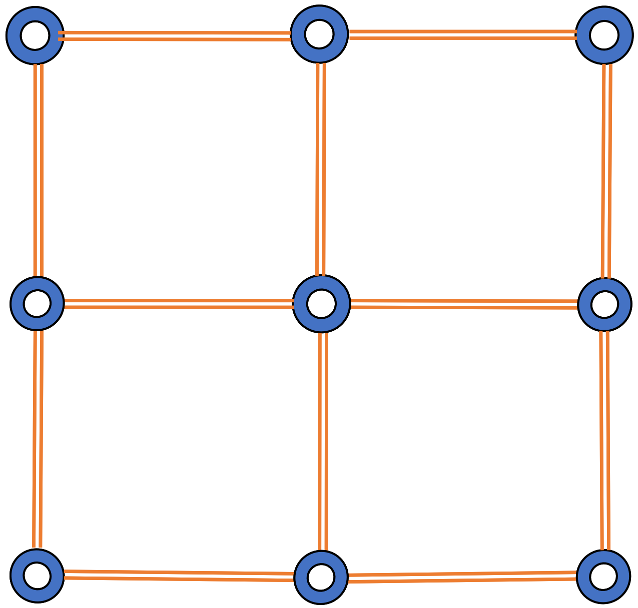


01 + 10   2 Atoms



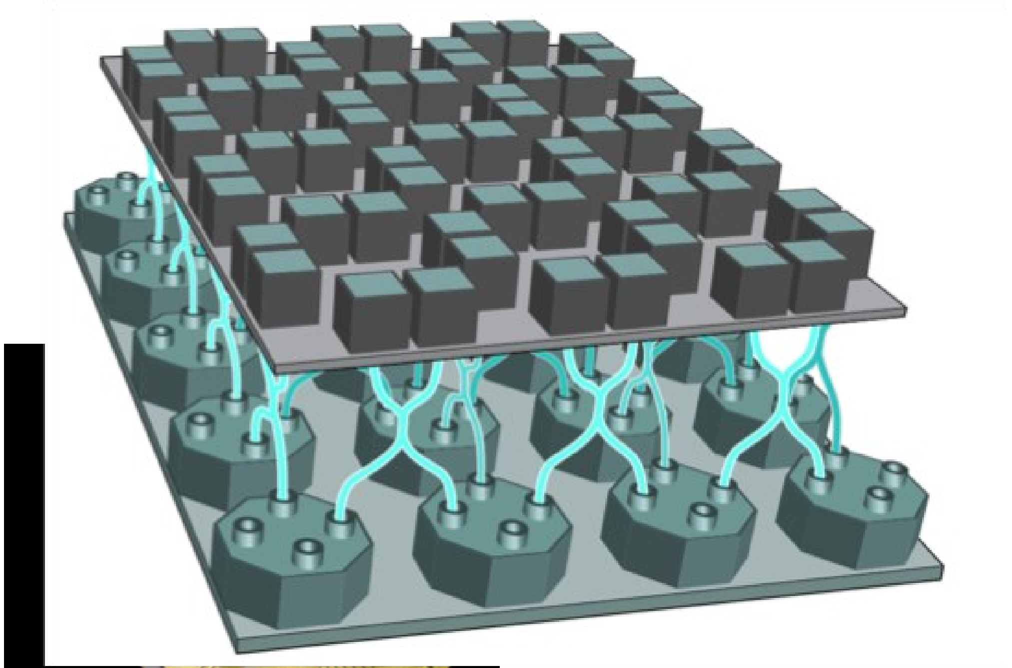
A single photon in a superposition of two paths can prepare two atoms in an entangled state

Building a Quantum Computer



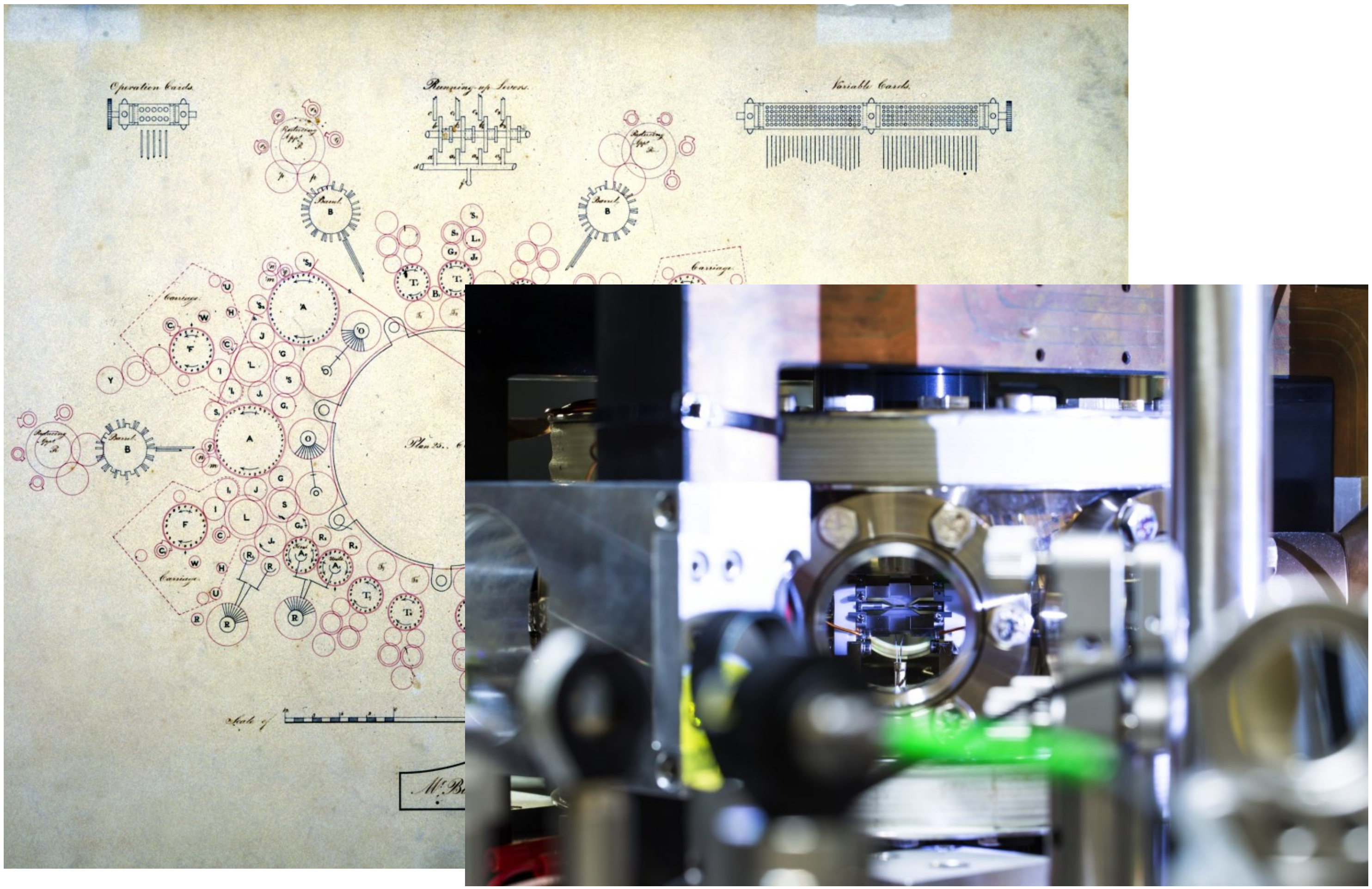
Network architecture enables an operational quantum computer.

It is possible to scale up this construct based on mastering control of entangling ions at different nodes using light, and storing and processing information in ions at each node.



What's the challenge?

If it is possible in principle….



What’s the challenge?

“Well, your quantum computer is broken in every way possible simultaneously.”

Superposition is a delicate phenomenon and disappears in a noisy environment.

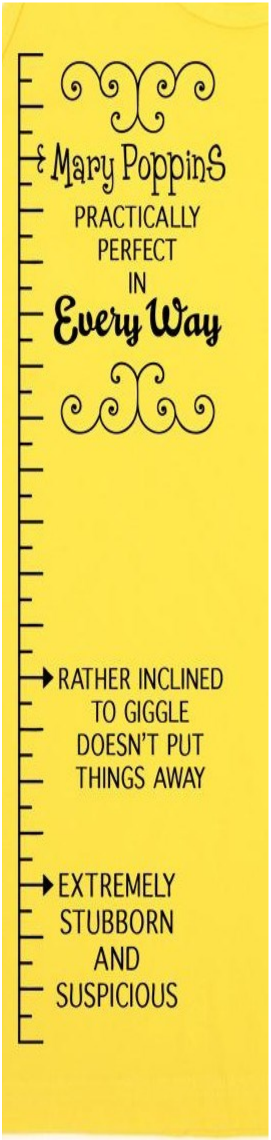
Network architecture enables errors and noise to be managed effectively.

Quantum Error Correction: #qubits

Good news:

Theorists long ago figured out that we can turn a whole bunch of badly-behaved qubits into a smaller number of practically perfect ones!

This is Fault Tolerant quantum computing.



'Logical' qubits

Physical qubits

Networked Quantum Computing: Connectivity

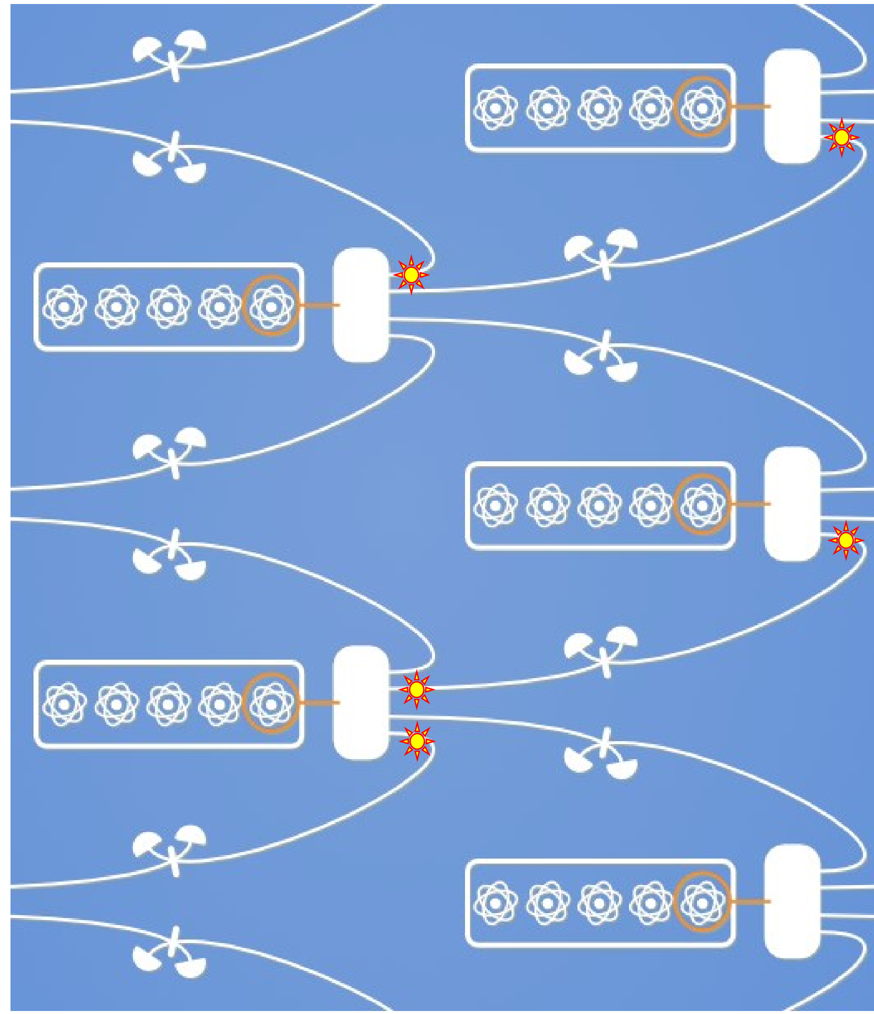
UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

NQIT Networked Quantum Information Technologies

Quantum Computing & Simulation Hub

Consortium of universities across UK & partner organisations (industry and government)

UKRI National Quantum Computing Centre



Platforms for Quantum Computing

Companies

Google

IBM

Microsoft

Companies are playing to their strengths

Technologies

- Ion traps
- Superconducting qubits
- NV centres in diamond
- Photons
- Impurities in Silicon
- Topological qubits

Research Centres

JQI – Joint Quantum Institute

CQT – Centre for Quantum Technologies

NQIT – Networked Quantum Information Technologies

EQUS – ARC Centre of Excellence for Engineered Quantum Systems

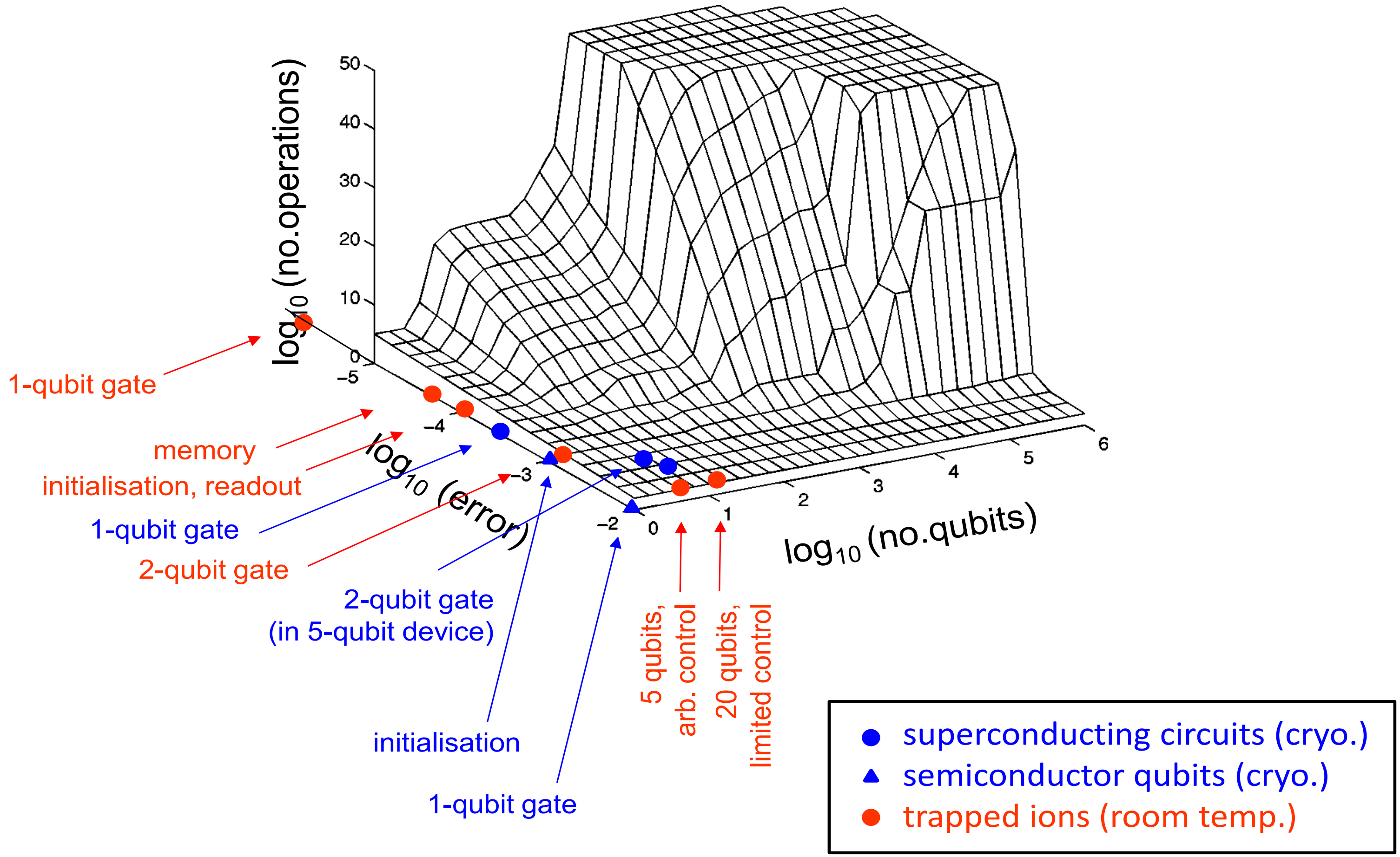
QuTech

ETH zürich

What's possible?

The QC mountain

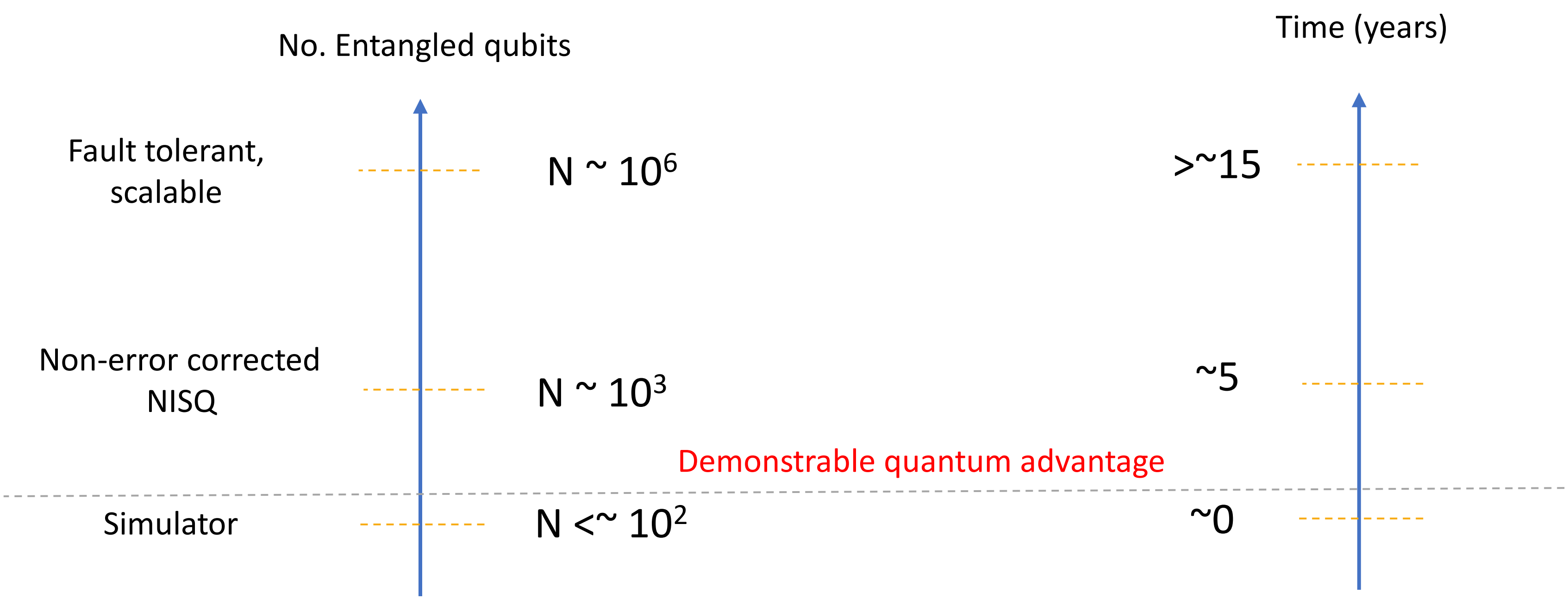
Component performance benchmarking



Points from David Lucas.
Graph from “Overhead and noise threshold of fault-tolerant quantum error correction,” A.M.Steane, PRA 2003.

Engineering for scale

A fully scalable quantum computer is some way off



What are the challenges?

- Delivering the systems engineering and manufacturing capabilities that are needed to scale up laboratory prototypes.
- Providing access to emulators/early NISQ machines for software/algorithm development for new applications.
- Scale up in engaging users, and identifying early adopters.

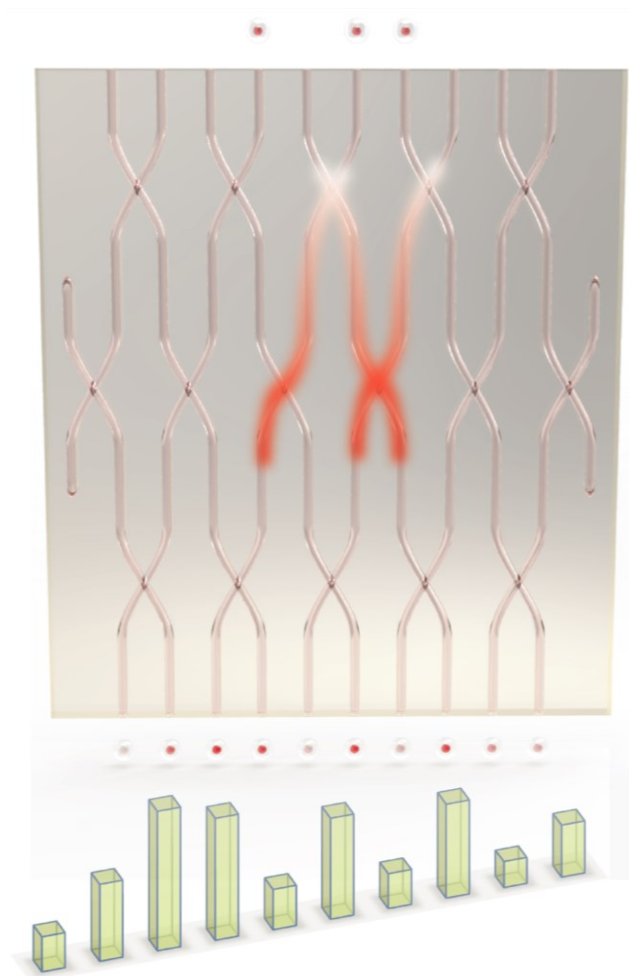
Near Term: feasible "Quantum Supremacy"

Boson Sampling

Algorithm to sample from a distribution that is hard to compute for a Turing Machine†

1. Require:
   a) Identical bosons
   b) Linear evolution
   c) Single boson detectors

2. Even approximately sampling from the boson distribution is (very likely) classically hard



Probability $\propto \left| Per(\Lambda) \right|^2$

†S. Aaronson, A. Arkhipov, "The computational complexity of linear optics", Proc. STOC 2011, pp. 333-342.

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Article

Quantum supremacy using a programmable superconducting processor

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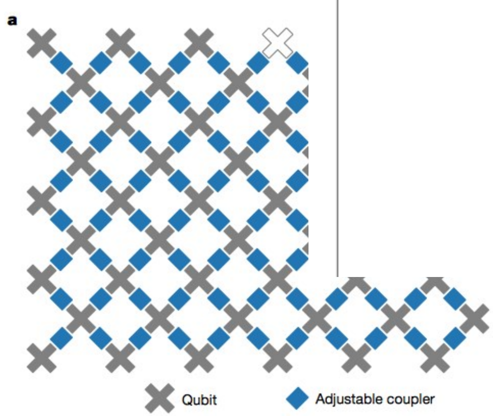
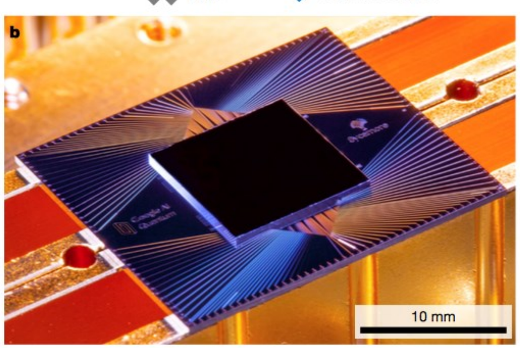
The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor[1]. A





Google AI Blog

The latest news from Google AI

REPORT

Quantum computational advantage using photons

Han-Sen Zhong[1,2,*], Hui Wang[1,2,*], Yu-Hao Deng[1,2,*], Ming-Cheng Chen[1,2,*], Li-Chao Peng[1,2], Yi-Han ...

+ See all authors and affiliations

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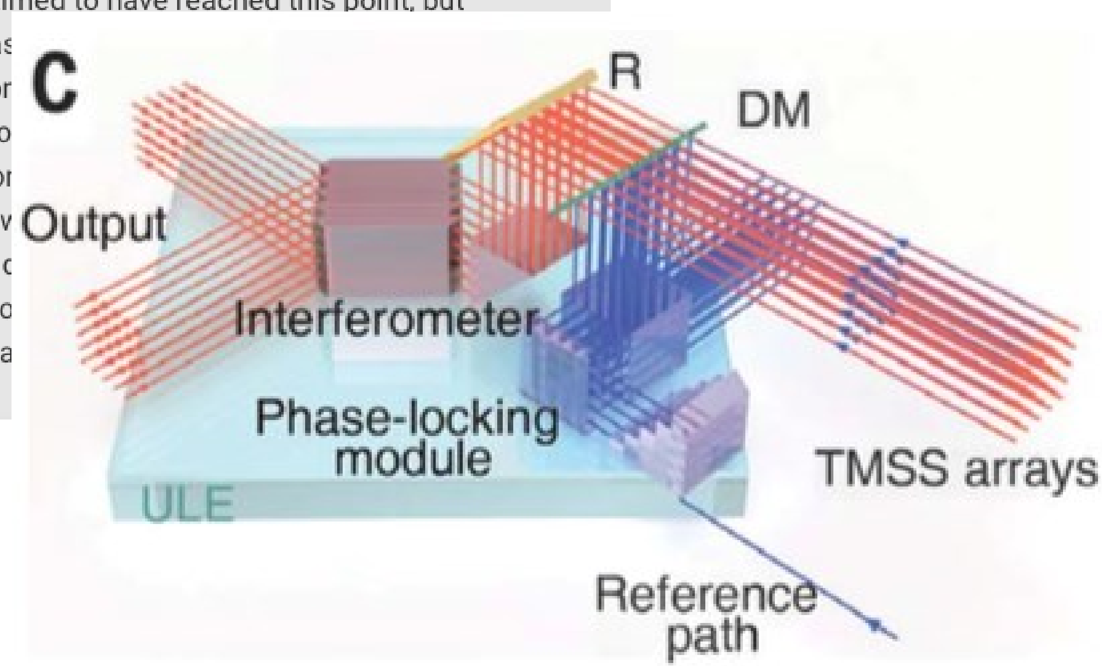
Article Figures & Data Info & Metrics eLetters PD

A light approach to quantum advantage

Quantum computational advantage or supremacy is a long-anticipated milestone toward practical quantum computers. Recent work claimed to have reached this point, but subsequent work managed to speed up the clas sample size–dependent loophole. Quantum cor one-shot experimental proof, will be the result o quantum devices and classical simulation. Zhor mode squeezed states into a 100-mode ultralov output using 100 high-efficiency single-photon c coincidence, yielding a state space dimension o rate that is about 10^{14}-fold faster than using sta and supercomputers.



Standards: Performance Measures

How to compare the performance of different quantum computers?

Entangling Gate Fidelity

Number of qubits

Connectivity

IBM Quantum Volume:

largest number of qubits on which you can build an arbitrary quantum state

Volumetric measures:

Width – number of register elements
Depth – number of successive operations

Opportunity

- Controllable large-scale quantum interference via entanglement is the resource for quantum computing
- This regime offers a transformation for IT.
- We already have a roadmap for building a quantum computer.
- There is an emerging community to deliver hardware, software and applications from users.