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

19th

Babbage Difference Engine

20th

Colossus at Bletchley Park

ENIAC

21st

Sunway TaihuLight System

Quantum 2.0

\(\frac{1}{2}\left|\psi\right\rangle + \frac{1}{2}\left|\phi\right\rangle\)
Certain problems are “hard” for Turing Machines – and “easy” for Quantum Machines

Complexity and Scaling

- Turing Machine
- Quantum Machine

<table>
<thead>
<tr>
<th>Complexity (Resources)</th>
<th>Size (No. bits)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Simulator</td>
<td>N ~ 10^2</td>
</tr>
<tr>
<td>NISQ</td>
<td>N ~ 10^3</td>
</tr>
<tr>
<td>Fault tolerant, scalable</td>
<td>N ~ 10^6</td>
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</table>

No. Entangled qubits
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)

Quantum Physics:
A switch may be OFF and ON

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

Quantum physics tells us there are more possibilities

0 and 1 is called a ‘superposition’ and the basis for quantum computing is the “qubit”
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.
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.
Theorists long ago figured out that we can turn a whole bunch of badly-behaved qubits into a smaller number of practically perfect ones!

**Good news:**

This is Fault Tolerant quantum computing.
Networked Quantum Computing: Connectivity

Consortium of universities across UK & partner organisations (industry and government)
## Platforms for Quantum Computing

**Companies**

- Google
- IBM
- Microsoft

**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

Companies are playing to their strengths.
What’s possible?
The QC mountain

Component performance benchmarking

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

\[ \text{Probability} \propto |\text{Per}(\Lambda)|^2 \]

Quantum supremacy using a programmable superconducting processor


Published online: 23 October 2019

The promise of quantum computers is that certain computational tasks might be executed exponentially faster on a quantum processor than on a classical processor. A
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 classical sample size-dependent loophole. Quantum computing, a one-shot experimental proof, will be the result of quantum devices and classical simulation. Zhou et al. mode squeezed states into a 100-mode ultralow output using 100 high-efficiency single-photon coincidence, yielding a state space dimension of 
rate that is about $10^{14}$-fold faster than using standard 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.