Quantum Computing & Simulation Hub

Quantum: a new era for computing?

BCS Bedford Branch, 14 September 2020

Rupesh Srivastava (User Engagement)

UNIVERSITY OF OXFORD

Part of UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Funded by UKRI Engineering and Physical Sciences Research Council

What we'll cover

1. The status and outlook for Quantum Computing & Simulation

2. The UK QT Programme

3. How to engage with Quantum Computing

Question:

Is Quantum Computing relevant yet and where do I start?

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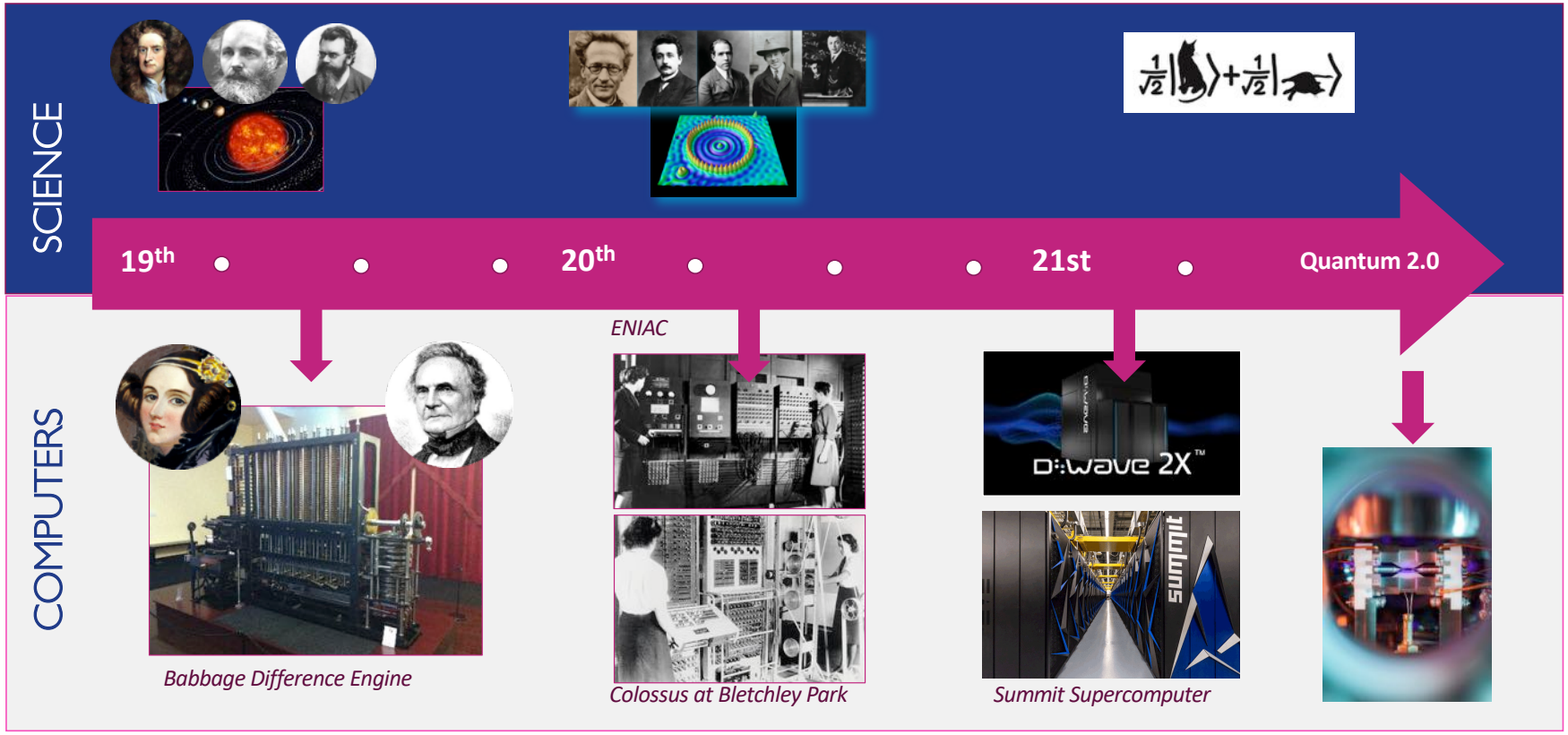
A recent history of science and computation



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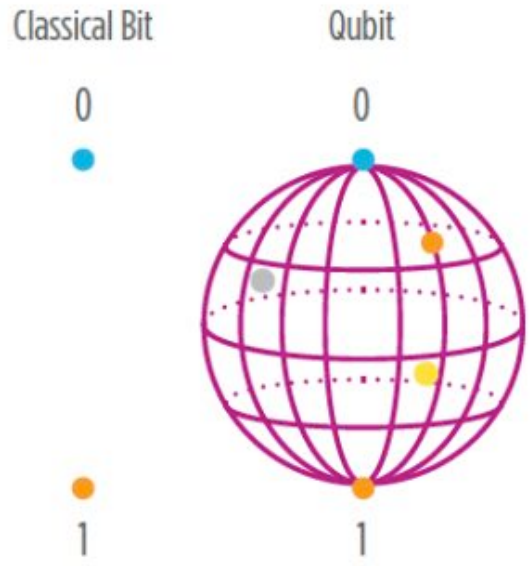
Quantum Computing and Qubits

Use and manipulate phenomena of quantum physics

- Superposition:
  - Qubits being in multiple states at the same time, e.g. ‘0’ and ‘1’
- Entanglement:
  - Grouped behaviour of multiple ‘qubits’

- In order to simulate N qubits requires 2^N classical bits

N	2^N	
3	8	easy!
20	~$1x10^6$	laptop
50	~$1x10^{15}$	supercomputer
300	~$2x10^{90}$	> atoms in known universe



(Source: Blackett Review, 2017)

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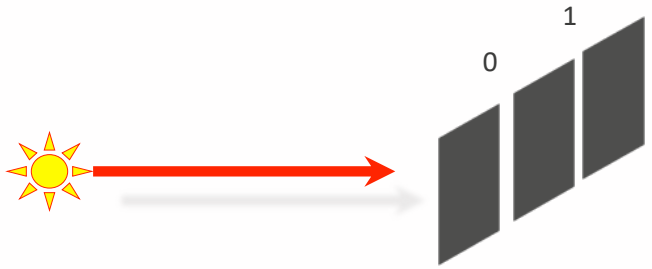
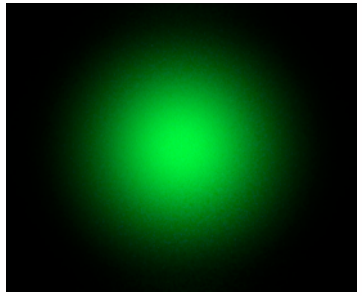
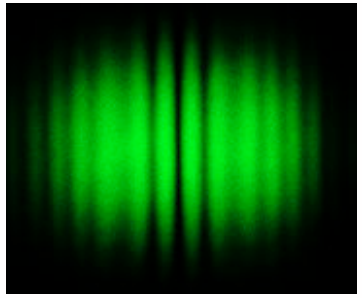
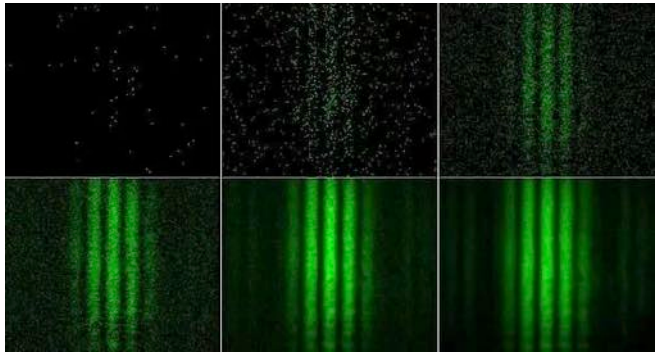
Illustrating superposition with light

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”

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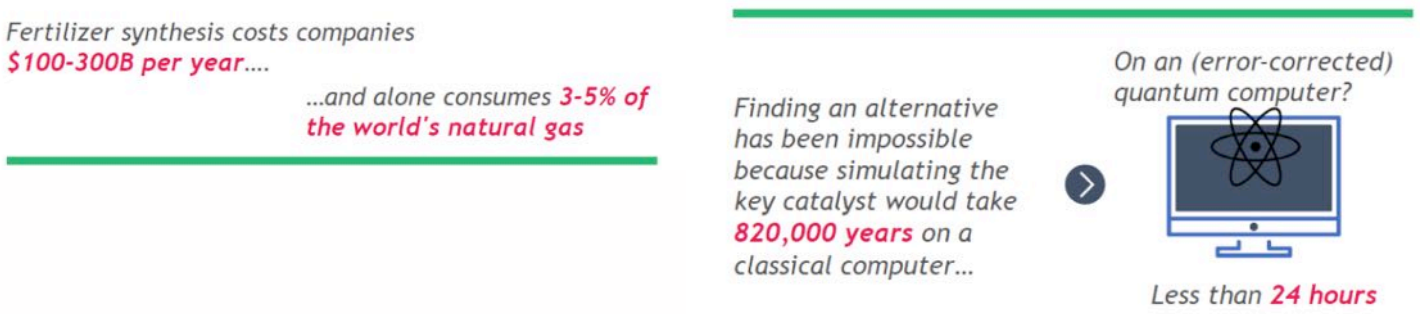
Why the excitement?

- A Quantum Computer's power doubles with every qubit added
  - Speedups beyond the capability of future digital computing
  - Able to solve 'hard problems'
  - Able to mimic real world quantum systems
- Expected high impact on most industry sectors, national economies, national security and research and discovery
- Estimated impact, $450-800bn operating income/yr*

*(Source: Where will Quantum Computers Create Value – And When?, BCG, 2019)



Source: The Business Potential of Quantum Computing, BCG @ Q2B, Dec 2019

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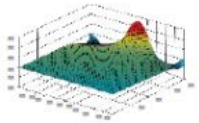
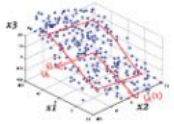
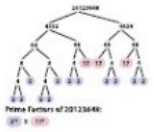
Why the excitement? (cont'd)

Problem archetype	Useful for ...	Industry applications
Combinatorial optimization 	... minimizing or maximizing an objective function such as finding the most efficient allocation of resources, or the shortest total distance among a set of points (e.g. the travelling salesman problem)	• Network optimization for airlines • Supply chain and logistics optimization • Portfolio optimization in financial services
Differential equations 	... modeling the behavior of complex systems involving fundamental laws of physics (e.g. Navier Stokes for fluid dynamics) and chemistry	• Fluid dynamics simulations for automotive and aeronautical design, and for medtech • Molecular simulation for specialty materials design and for drug discovery
Linear algebra 	... machine learning tasks involving matrix diagonalization such as clustering, pattern matching and principal components analysis (PCA), as well as support vector machines (SVMs) which are ubiquitous in applications across industries	• Risk management in quantitative finance • DNA sequence classification • Marketing and customer segmentation
Factorization 	... cryptography and computer security where the most common protocols today (e.g. RSA) rely on the infeasibility (for classical computers) of factoring the product of two large prime numbers.	• Decryption and codebreaking, e.g. for governments

(Source: The Business Potential of Quantum Computing, BCG, 2019)

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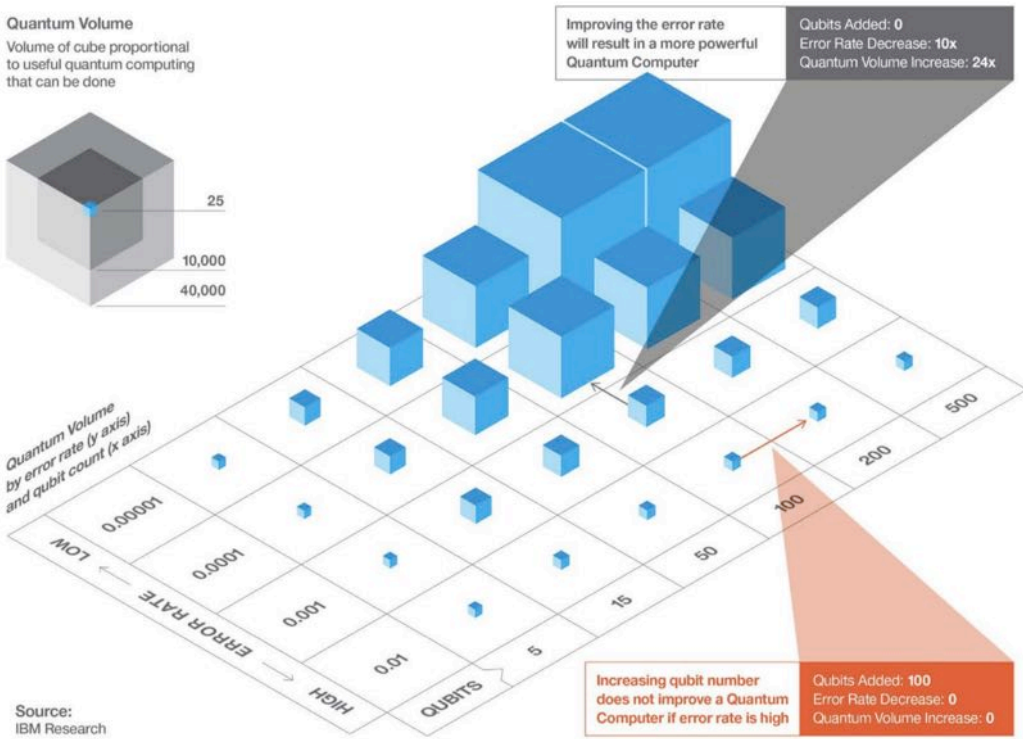
But not so fast …

- QC's and Qubits are fragile, difficult to control, difficult to read, full of errors, slow and expensive
- Quantum Error Correction (QEC) enables a Universal Fault Tolerant Quantum Computer (UFT) with 'logical qubits' but requires large numbers of physical qubits
- The QEC 'overhead' depends on the quality of the physical qubits



(Source: IBM, 2018)

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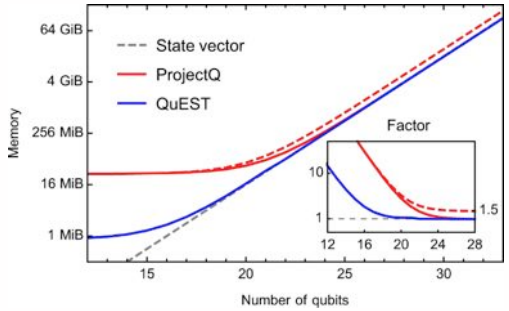
In the Near Term …

Until we have Universal Fault Tolerant QC:

- Digital emulators of Quantum Computers
- Noisy Intermediate Scale Quantum Computing (NISQ)
- Simulators and Annealers
- Quantum Inspired Classical Computing



(Source: QuEST and High Performance Simulation of Quantum Computers, T Jones e.a. Nature, 2019)

Quantum Computing in the NISQ era and beyond

John Preskill

Institute for Quantum Information and Matter and Walter Burke Institute for Theoretical Physics, California Institute of Technology, Pasadena CA 91125, USA

30 July 2018

Noisy Intermediate-Scale Quantum (NISQ) technology will be available in the near future. Quantum computers with 50-100 qubits may be able to perform tasks which surpass the capabilities of today's classical digital computers, but noise in quantum gates will limit the size of quantum circuits that can be executed reliably. NISQ devices will be useful tools for exploring many-body quantum physics, and may have other useful applications, but the 100-qubit quantum computer will not change the world right away — we should regard it as a significant step toward the more powerful quantum technologies of the future. Quantum technologists should continue to strive for more accurate quantum gates and, eventually, fully fault-tolerant quantum computing.

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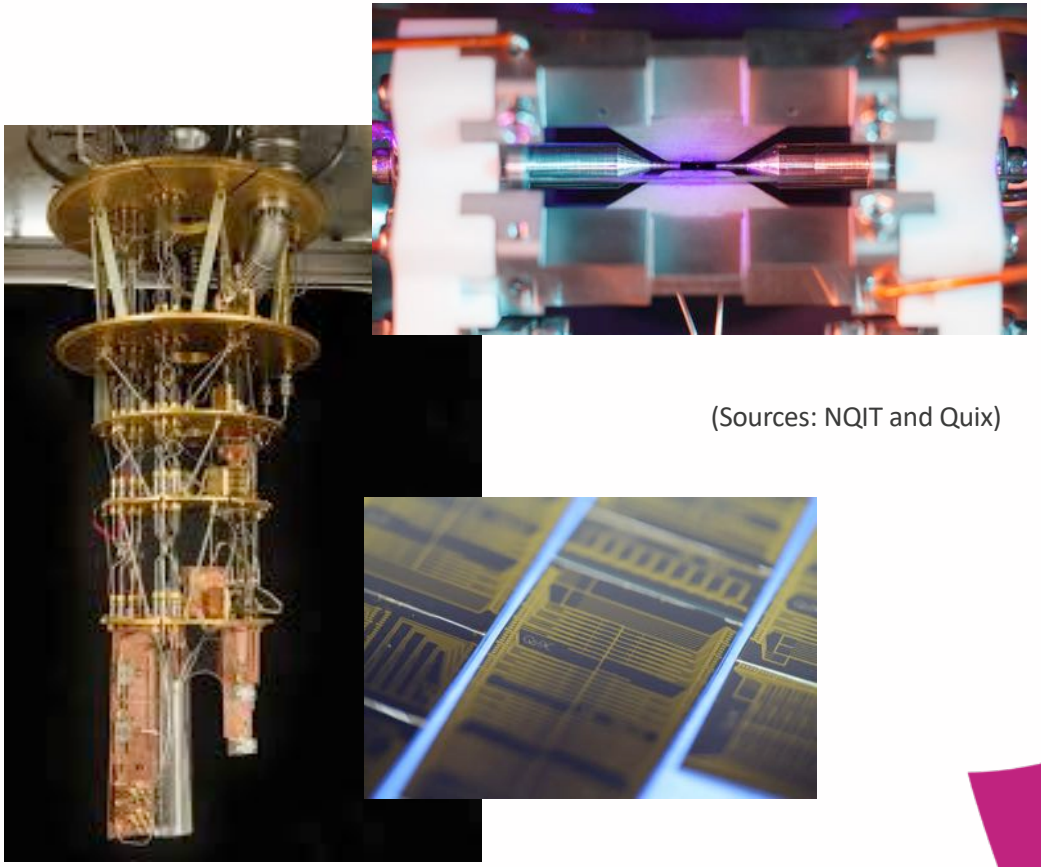
The NISQ Hardware Technologies

- Circuit based QC:
  - Superconducting circuits*
  - Ion traps*
  - Photonic*
  - Solid state silicon
  - NV centres in diamond
  - Cold atoms
  - Topological

All scalable to UFT (?)

* NISQ technology now



(Sources: NQIT and Quix)

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The available NISQ's

- IBM Q, 18 QC's online (free or paid) with up to 53 qubits
- Google Sycamore, access on request, up to 54 qubits
- Rigetti, access on request or via AWS Braket, up to 32 qubits
- IonQ, access on request or via AWS Braket, up to 11 qubits
- Honeywell, access TBA or via AWS Braket, up to 6 qubits
- Xanadu, 8/12 qubits with 24 announced, access on request
- QuTech's Quantum Inspire, open access with up to 5 qubits

30+ new ventures worldwide building quantum computer systems

… including 6 in the UK

Announced:

- UK National Quantum Computing Centre
- Finland VTT to acquire a National Quantum Computer
- Germany's national quantum plan (at least 2 national QC's) … etc

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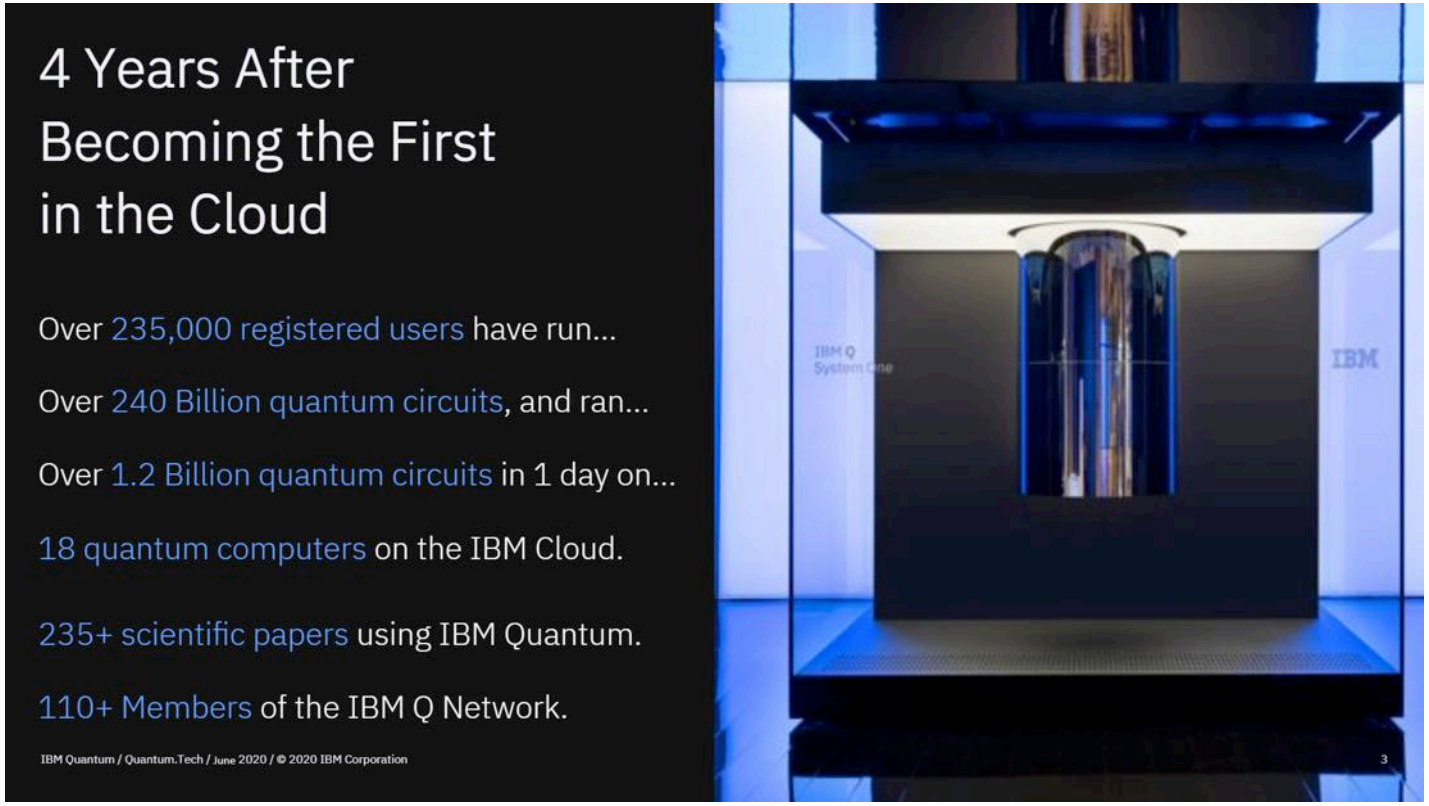
IBM Q as an example



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(Source: IBM, 2020)

What about usefulness: Google's Quantum Supremacy

- Google used its 54* qubit Sycamore processor
- Non-error-corrected quantum computer (i.e. a NISQ)
- In collaboration with NASA ran a well defined computational task (RNG)
- The experiment took 200 seconds
- Google determined that it would take the world's fastest supercomputer 10,000 years to produce a similar output

* with 53 qubits working

- IBM's response included a proposal that would use the world's most powerful supercomputer using 250 petabytes of hard-disk space running for 2.5 days

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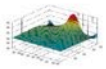
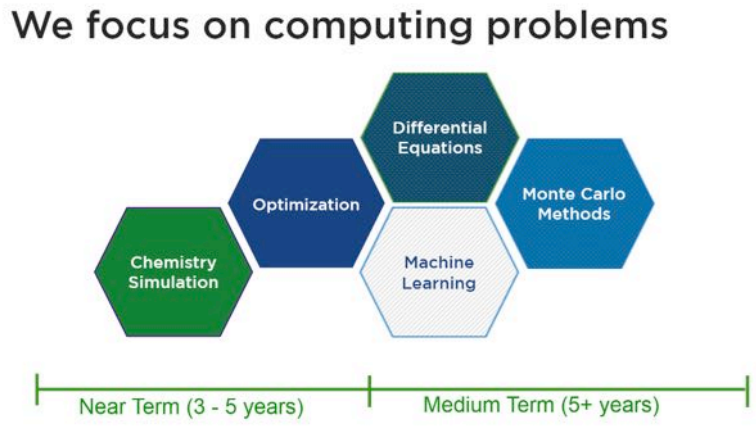
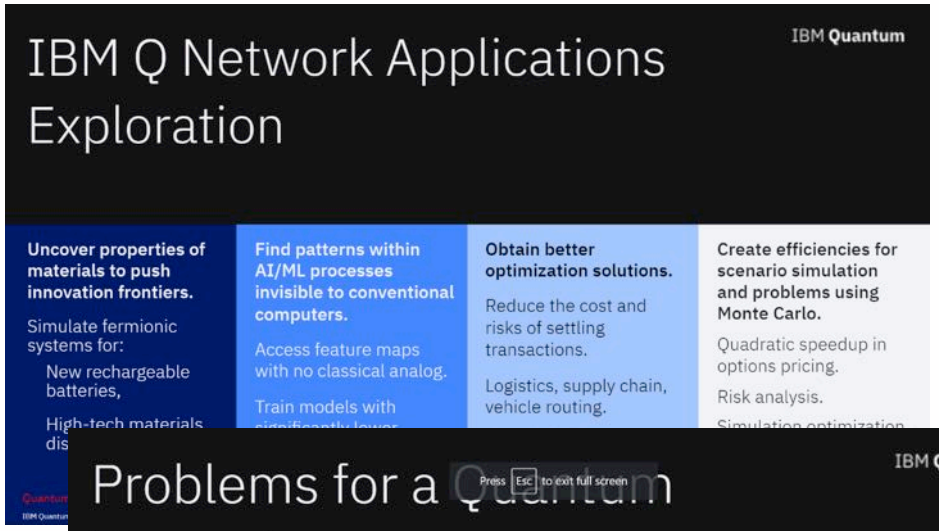
The Practical Use Cases

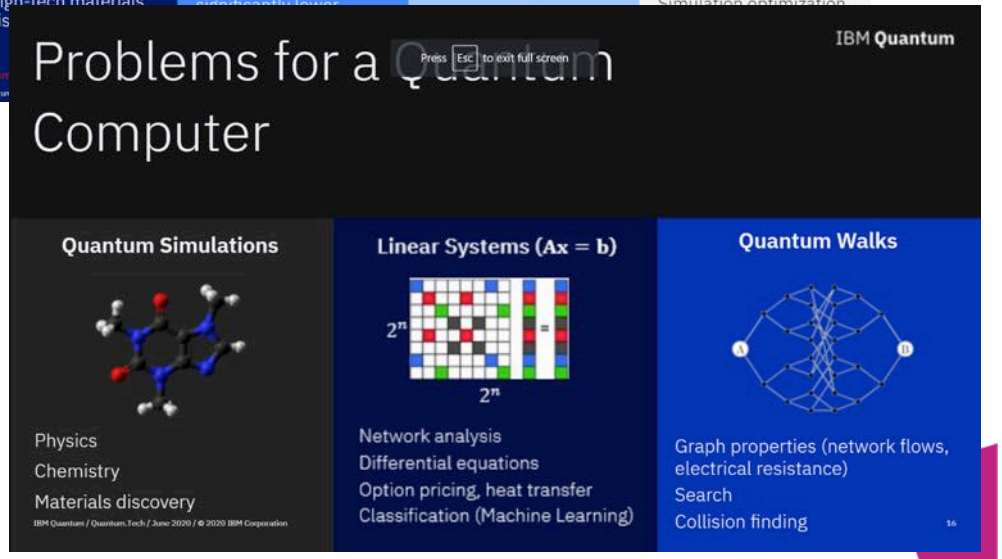
Problem archetype	Useful for ...	Industry applications
Combinatorial optimization 	... minimizing or maximizing an objective function such as finding the most efficient allocation of resources, or the shortest total distance among a set of points (e.g. the travelling salesman problem)	• Network optimization for airlines • Supply chain and logistics optimization • Portfolio optimization in financial services
Differential equations 	... modeling the behavior of complex systems involving fundamental laws of physics (e.g. Navier Stokes for fluid dynamics) and chemistry	• Fluid dynamics simulations for automotive and aeronautical design, and for medtech • Molecular simulation for specialty materials design and for drug discovery
Linear algebra 	... machine learning tasks involving matrix diagonalization such as clustering, pattern matching and principal components analysis (PCA), as well as support vector machines (SVMs) which are ubiquitous in applications across industries	• Risk management in quantitative finance • DNA sequence classification • Marketing and customer segmentation
Factorization 	... cryptography and computer security where the most common protocols today (e.g. RSA) rely on the infeasibility (for classical computers) of factoring the product of two large prime numbers.	• Decryption and codebreaking, e.g. for governments

(Source: The Business Potential of Quantum Computing, BCG, 2019)



(Source: QCWare, 2020)





(Source: IBM, 2020)

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One more thing … encryption

- NISQ's are not a threat to most current encryption methods

  … but UFT Quantum Computers are!

- Key risks:
  - Current data can be stored for future decryption
  - No quantum safe encryption has yet been identified
  - Re-encrypting existing data takes time
- From the National Cyber Security Centre:

  The NCSC acknowledges the serious threat posed by quantum computation to currently used forms of asymmetric cryptography, particularly key agreement algorithms.

  We strongly recommend a considered approach to transitioning to quantum-safe cryptography, as and when algorithms and parameter sets become stable and are standardised.

https://www.ncsc.gov.uk/whitepaper/quantum-safe-cryptography

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The Development Tools and Environments

- IBM Quantum Experience and Qiskit
- Cirq and ProjectQ, promoted by Google AI
- Rigetti's Forest platform with Quil
- Amazon's Braket multi-vendor platform and environment
- Microsoft's Quantum Development Kit including Q#
- Atos/STFC Quantum Learning as a Service
- QuEST open source Quantum Simulation Kit from Oxford
- Deltaflow, River Lane's cross platform operating system
- Quantum Inspire platforms from QuTech in Delft
- Zapata's Orquestra, a unified quantum operating environment
- Xanadu's Pennylane and Strawberry Fields python libraries
- Baidu's Paddle Quantum and many more …

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The Quantum Software Developers

	D-Wave	Google Cirq	IBM Qiskit	Microsoft	Rigetti	AWS	Atos
1QBit	X		X	X	X	X	
Agnostiq			X				
AIQTech			X				
Beit			X				
Boxcat			X				
Cambridge Quantum Computing		X	X	X			
Entropica Labs			X	X	X		
Grid			X				
GTN				X			
Horizon Quantum Computing					X		
HQS Quantum Simulations		X		X	X		
JoS Quantum			X				
Labber Quantum			X				
Max Kelsen			X				
Multiverse				X			
MDR	X		X				
Netramark			X				
OTI Lumionics	X			X	X		

	D-Wave	Google Cirq	IBM Qiskit	Microsoft	Rigetti	AWS	Atos
ProteinQure	X		X	X	X		
QC Ware	X	X	X	X	X	X	
Q-CTRL			X		X		
QSimulate						X	
Qu & Co			X	X			
Quantastica					X		
QuantFi			X				
Quantum Benchmark		X	X				
Quantum Machines			X				
Qubit Engineeering				X			
Quemix			X				
Qulab				X	X		
QunaSys			X	X			
QxBranch	X				X		
Rahko			X	X		X	
Rigetti						X	
Riverlane Research				X	X		
Solid State AI			X	X			
Strangeworks			X	X	X		
TradeTeq			X				
Xanadu				X		X	
Zurich Instruments			X				
Zapata Computing		X	X	X	X	X	X

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(Source: Quantum Computing Report)

Quantum Technologies in the UK

- Long history of outstanding science and QT pioneers
- A world-class advanced technology sector
- A UK National QT Programme since 2013
- Blackett Report in 2017
- HoC Science & Technology Committee Report, 2018
- UK QTP Phase 2 started in 2019

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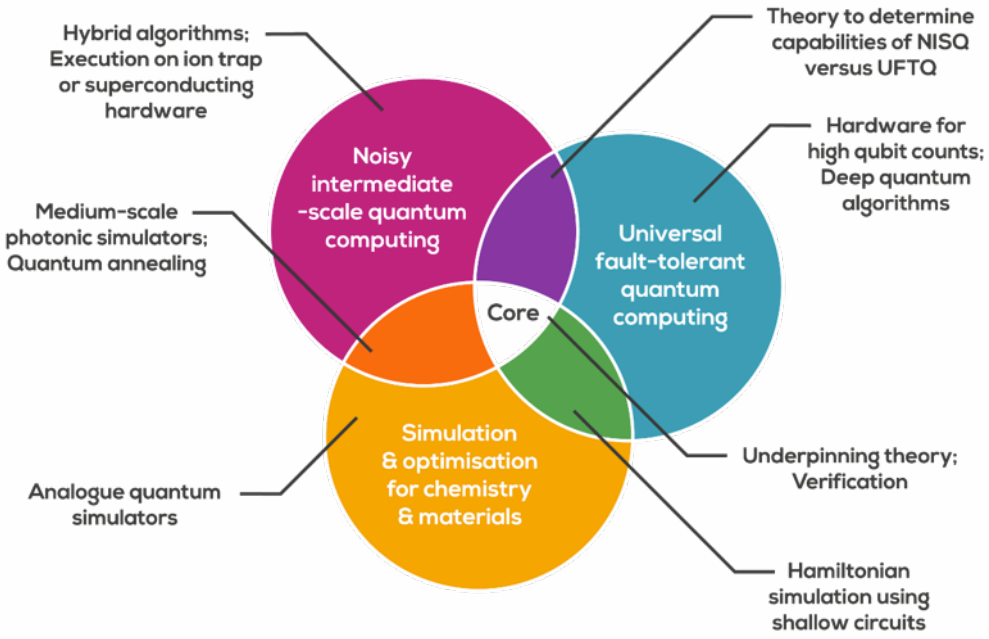
UK National QT Programme, 10 years, £1 billion

- Four Quantum Technology Hubs
  (Sensing, Imaging, Communications, Computing & Simulation)
- Skills and Training programme
- Industrial Strategy Challenge Fund for Industry-led Innovation
- National Quantum Computing Centre
- Strategic Partnerships and International participation
- 10-year Quantum Strategy led by UK Government

2019 – 2024 The QCS Hub

- The UK National Quantum Computing & Simulation Hub
- Five-year research and technology programme with £25m funding, following on from the 2014-2019 NQIT Hub
- Objective: to create a quantum information economy in the UK
- Focus on QC&S technologies, both near-term (NISQC) and long-term (UFTQC)
- 17 participating universities, 43 Co-Investigators, led by Oxford
- 28 companies and organisations offering support
- Supporting the UK National Centre for Quantum Computing



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QCS Hub Partners

Academic partners

Industrial partners

Airbus Defence & Space
BP
BT
Cambridge Quantum Computing Limited
Creotech Instruments SA
D Wave Systems
Defence Science & Tech Lab
Element Six
Fraunhofer Institute
GlaxoSmithKline
Gooch & Housego
Heilbronn Institute for Mathematical Research
IQE Ltd
Johnson Matthey
M Squared Lasers
National Cyber Security Centre
National Physical Laboratory
Oxford Instruments Ltd
Oxford Quantum Circuits
Oxford Sciences Innovation
QinetiQ
Quantum Machines
Quantum Motion
QxBranch
Rigetti & Co
Rolls-Royce
The Alan Turing Institute
Trakm8 Ltd

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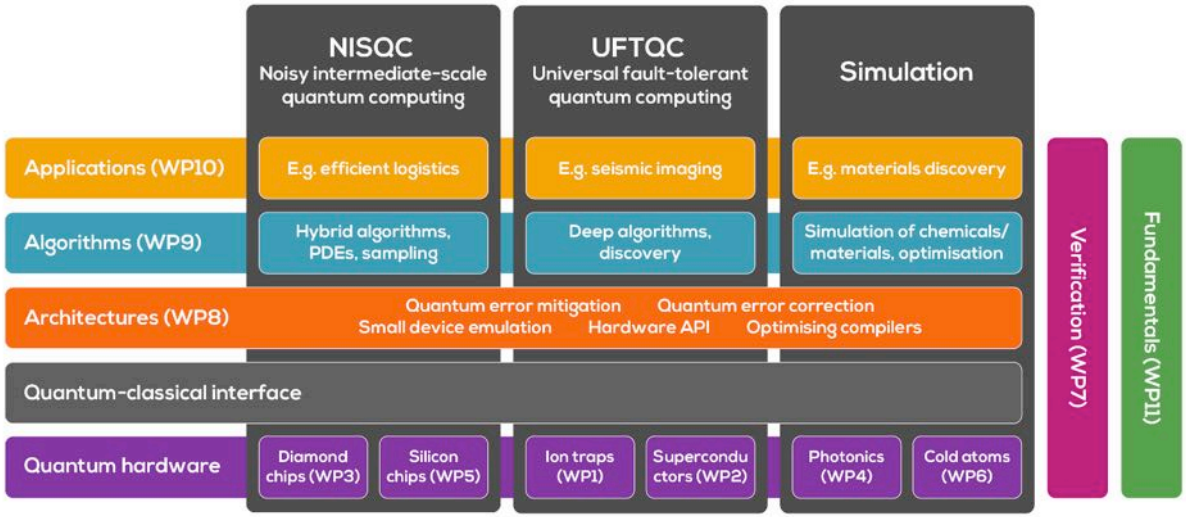
QCS Hub Work Programme

- Scaling: build more and better qubits cheaper
- Hybrid systems: Classic for the mundane and the precise
- Software stack
- Algorithms & Applications
- Development environment
- Quantum networking
- Standards
- User communities and Skills



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Engineering and Physical Sciences Research Council

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2014-2019 Achievements

- Photonically-networked ion trap architecture: node-node connectivity demonstrated with a world-leading combination of rate and fidelity
- New benchmarks for speed and precision of quantum logic operations
- Modular quantum optical circuits for processing and simulation
- Unique deterministic NV centre-writing capability
- Unique superconducting qubit architecture
- Blind quantum computing and verification concepts
- World's fastest emulator, QuEST
- Verifiable Quantum Random Number Generator
- Responsible Research and Innovation studies in QC
- Vibrant network of over 100 companies engaged
- Encouraged and supported seven spinouts
- International advocacy and industrial engagement
- Skills and training in quantum science, technology and entrepreneurship

NQIT Networked Quantum Information Technologies

OXFORD HIGHQ

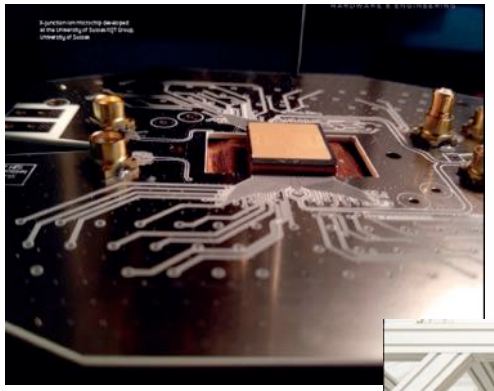
OQC

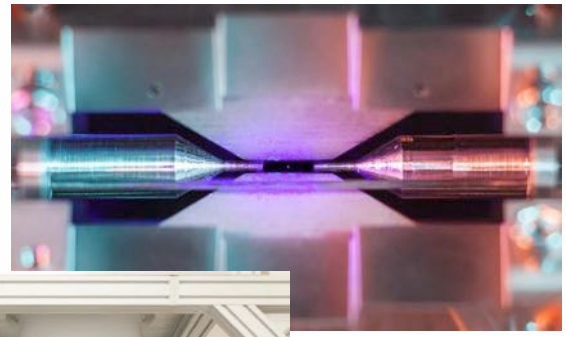
QUANTUM MOTION

Universal Quantum

QD Quantum Dice

OXFORD IONICS





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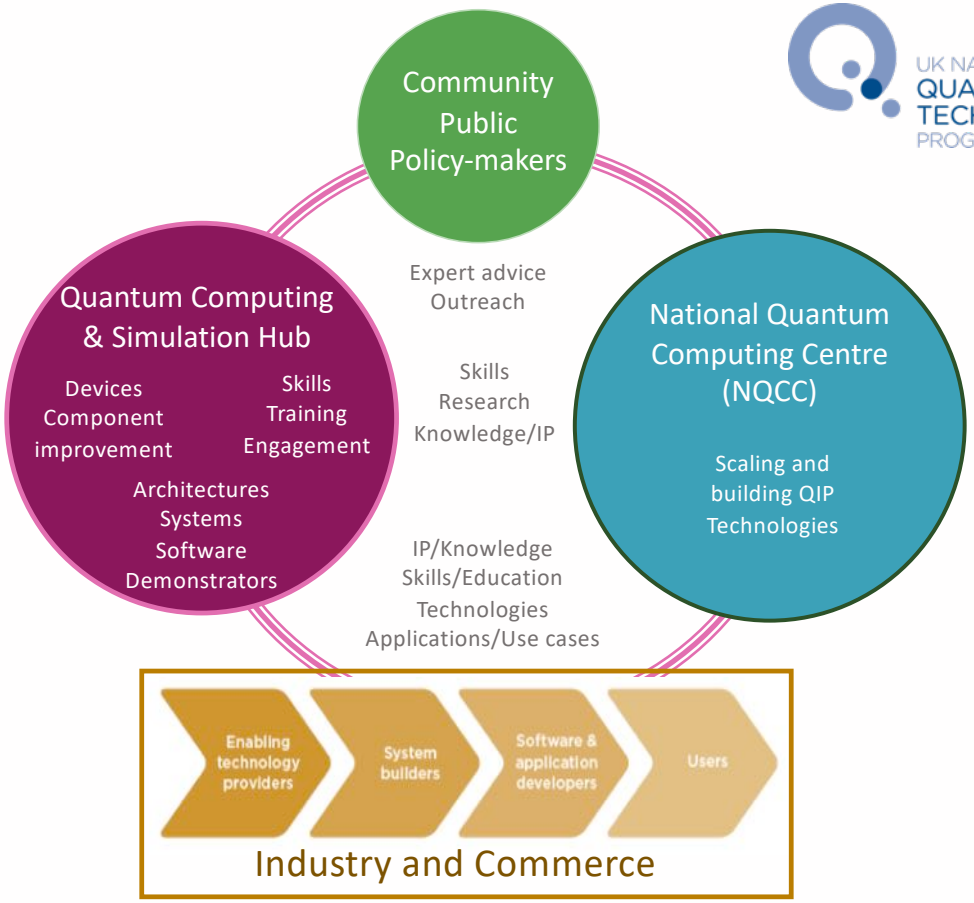
QCS Hub Context

- The Hub creates the building blocks for the NQCC and industry to scale and exploit
- Industry Engagement with all parts of the value chain: enabling technologies, system integrators, application developers and users
- Partnerships with IBM, Google a.o.
- Encouraging quantum readiness (QRP) and quantum literacy in industry and with the public
- Encourage quantum literacy through outreach (Quantum City)
- Support all parts of the UK National Quantum Technologies Programme: Technology Hubs, Skills Hubs, Innovate UK ISCF, KTN Quantum SiG, NPL, The National Quantum Computing Centre, policy makers and sponsors including Dstl and NCSC



UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

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Engineering and Physical Sciences Research Council

Department for Business, Energy & Industrial Strategy

National Cyber Security Centre a part of GCHQ

Innovate UK Knowledge Transfer Network

Innovate UK

NPL National Physical Laboratory

[dstl]

The UK Quantum Industry Landscape

Hardware

Software

Security

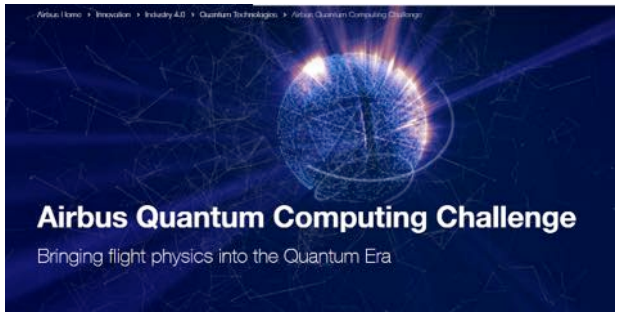
Systems

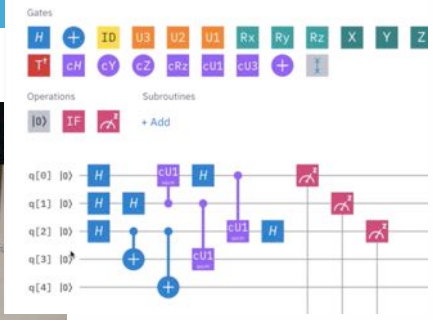
Users

(For illustration only, no relationships implied)

Engagement Opportunities

- Explore Quantum Algorithm Zoo
  (https://quantumalgorithmzoo.org/)
- Experience online systems
- Learn a development environment:
  online, q-hackathons, workshops
- Enter a Challenge: Rigetti, IBM, Airbus, …
- UK Quantum Showcase (6 Nov, London)





Quantum Inspire

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How the QCS Hub can help

We collaborate with suppliers, integrators and developers, prospective users, entrepreneurs and investors:

- Partnership Resource Funding for collaborative projects
- Publish Reports and run a Quantum Readiness Programme
- Partnerships with system vendors, e.g. IBM Q
- Access to the research community
- Public outreach through Quantum City, a UKNQTP collaboration

To get involved, please contact the engagement team at qcshub.org



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www.qcshub.org

Thank You!

Part of UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

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