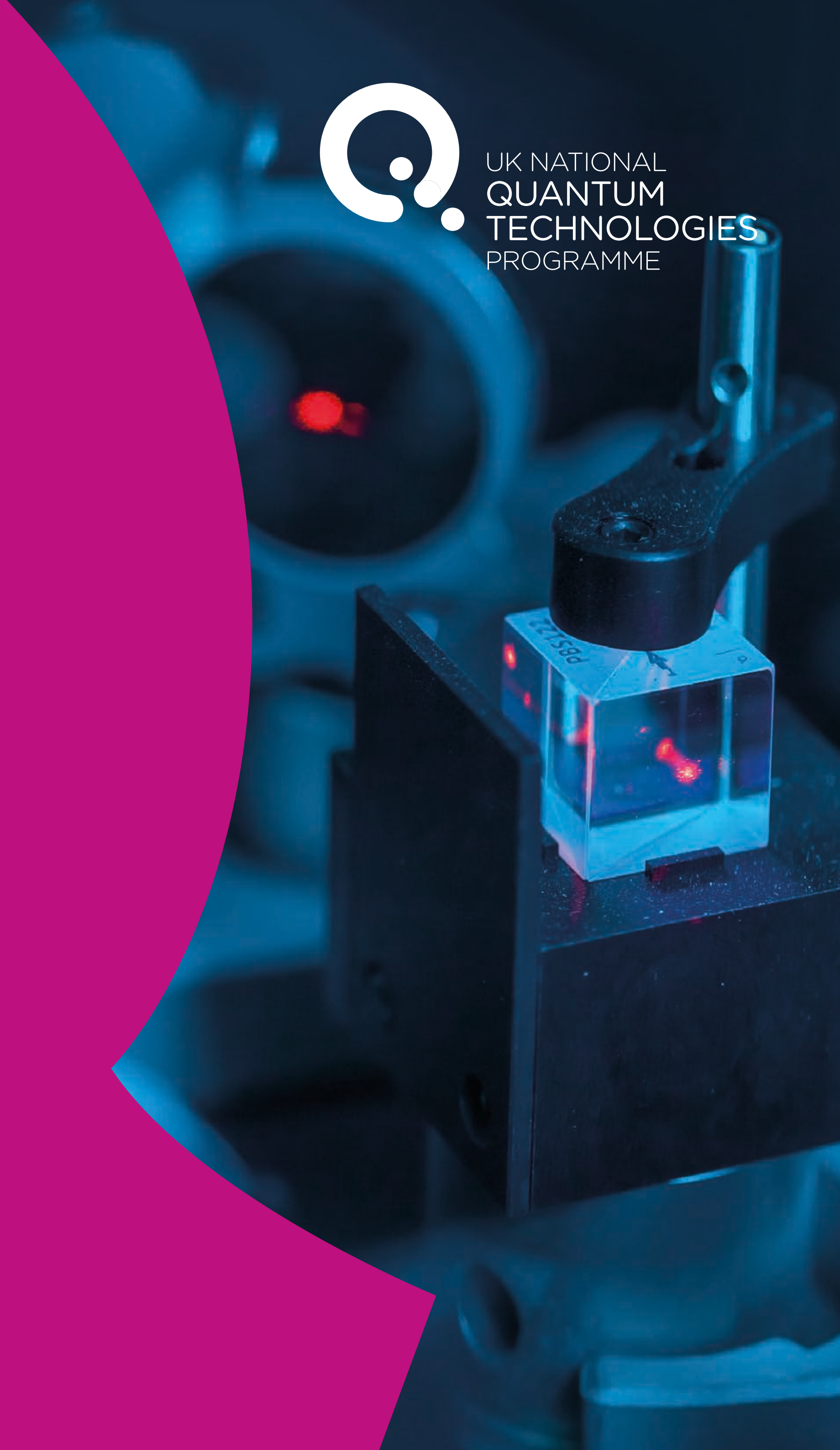
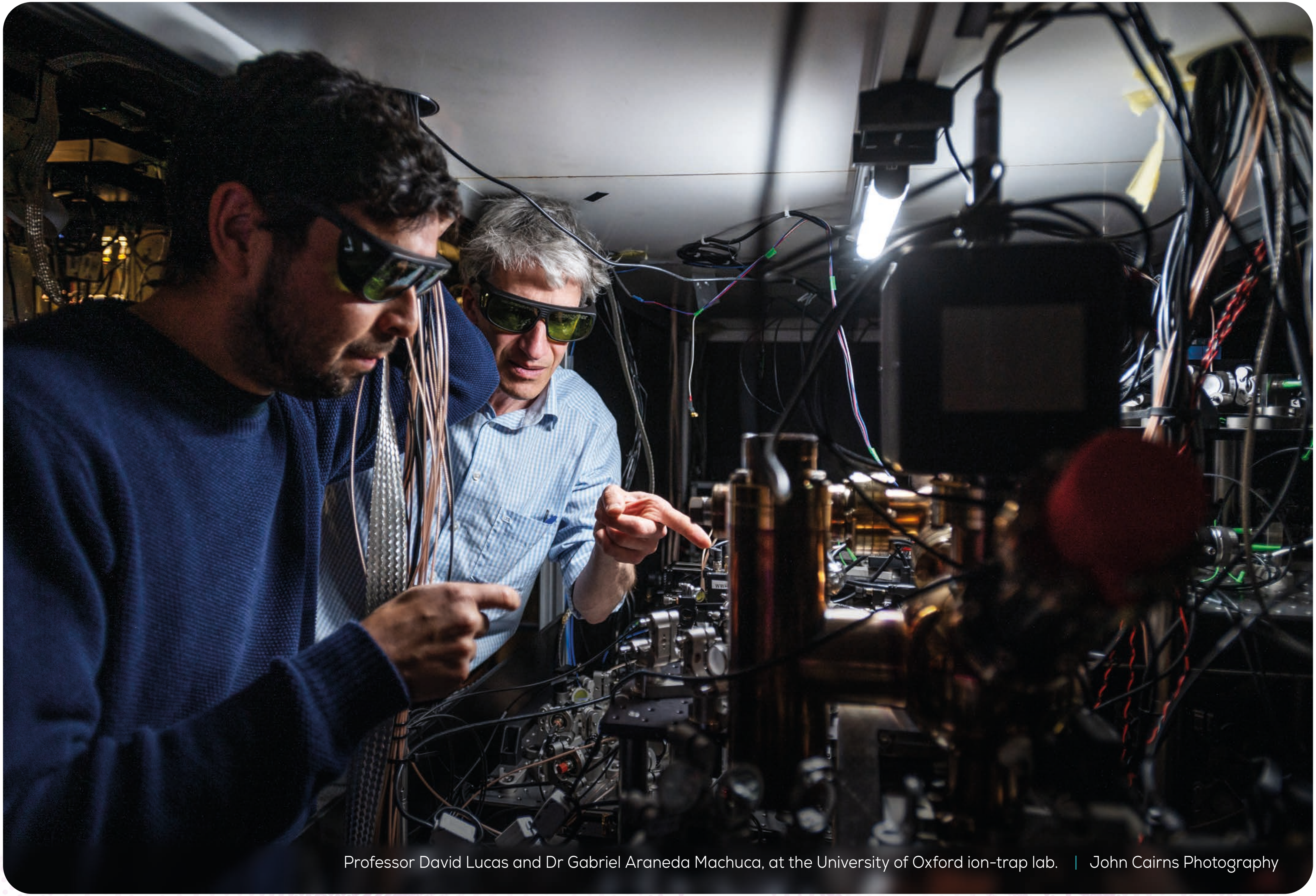
Quantum
Computing &
Simulation Hub

Final Report



UK NATIONAL
QUANTUM
TECHNOLOGIES
PROGRAMME



Professor David Lucas and Dr Gabriel Araneda Machuca, at the University of Oxford ion-trap lab. | John Cairns Photography

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Introduction

The UK has a thriving National Programme in Quantum Technologies. For a decade EPSRC has funded Hubs in the field of quantum computing which, alongside other quantum technology hubs, have been a key part of the landscape.

A quantum computing industry is emerging, and stable roadmaps are charting a path to useful quantum computers. Such machines will underpin a substantial new IT industry, and the new quantum strategy, along with the associated quantum missions, shows the commitment the UK has to this.

It has been a privilege to have been part of the leadership teams of both the Quantum Computing and Simulation Hub (QCS) and its predecessor the Networked Quantum Information Technologies Hub (NQIT), and to help our skilled students, researchers, academics and support teams deliver new research, insights and innovations. These have led to spinouts, new products, leading results, and people with the skills needed to take the field forward.

Over the past five years, the QCS Hub has made significant progress in advancing quantum computing technologies. Our research, spanning across multiple hardware platforms, has pushed the boundaries of what is possible in terms of performance, scalability, and integration. Alongside this, we have made substantial progress in software development, focusing on areas critical to the realization of practical quantum computing systems.

The following pages showcase the QCS Hub's achievements in these areas, as well as highlighting our commercial and industrial impact, successful collaborations, and our commitment to responsible research and innovation. We also look at our efforts in building a strong foundation for the future of quantum computing in the UK.

This report contains what is necessarily a small snapshot of this endeavour and I would like to thank all those involved in preparing this. I would also like to thank all of the QCS Hub team for their work on the project. We benefited greatly from the strong foundations that NQIT created, and our thanks extend to those involved.

I would also like to thank the members of our Technical Advisory Board - Rainer Blatt (University of Innsbruck), Jiarong Dawn Chan (EPSRC), Michael Cuthbert (National Quantum Computing Centre), David DiVincenzo (Juelich Research Center), Helen Margolis (NPL), Gillian Marshall (QinetiQ), Mark Parsons (University of Edinburgh), Krysta Svore (Microsoft), and Cheryl W (GCHQ) - for their valuable guidance during the life of the Hub.

I hope you find the report useful, and encourage you to get in touch if you would like to find out more.

Dominic

Professor Dominic O'Brien
QCS Hub Director

Hub Overview

Introduction

The UK Hub in Quantum Computing & Simulation (QCS Hub) is a collaboration between 17 UK universities and 27 industrial partners, and is one of the four hubs within the UK National Quantum Technologies Programme. Over the past five years, we have been working with an extensive network of academic, industrial, and governmental partners, focusing on the critical research challenges for quantum computing, across a broad range of hardware and software disciplines.

As well as addressing the technical challenges in providing quantum computing and simulation at scale, the Hub engages with industries, end users, government, and the general public. Our aim has been to accelerate progress within quantum computing and ensure that the UK is a leader in the emerging global quantum information economy.

Heritage

The QCS Hub is part of the second phase of the UK National Quantum Technologies Programme. It was preceded by the Networked Quantum Information Technologies Hub (NQIT) which ran from 2014-19. Among its many achievements, NQIT developed a photonically-networked ion trap architecture demonstrating node-to-node connectivity with a world-leading combination of rate and fidelity; NQIT also set new benchmarks for the speed and precision of quantum logic operations. Engaging with over 100 companies, NQIT encouraged and supported seven technology spinouts. Building on the expertise and achievements of the previous hub, the QCS Hub began in December 2019 with the ambition to create a quantum information economy in the UK.

Research

The Hub's scientific research spans the full stack of quantum computing (QC) hardware and software, and this is made possible by the broad expertise of both our researchers and partners. Our work on hardware has included a range of qubit technologies for both near-term and larger-scale quantum computers and simulators; our work on software and applications has involved developing algorithms and protocols for how such machines could be used, as well as techniques to verify their operation. We have also studied the architecture of quantum computers and developed emulation techniques to allow future applications to be tested.

Our programme has included distinct work packages, each focusing on a different area of quantum computing technology. These areas of investigation, discussed in more detail later in this publication, include:

- Ion trap processors
- Superconductors
- Diamond node chips
- Photonics
- Silicon quantum processors
- Cold Atoms
- Verification, Validation and Benchmarking
- Architectures, Control and Emulation
- Algorithms & Fundamentals
- Applications

Within the Hub, we hold regular six-monthly Project Forum events. These all-hands events have brought the whole Hub community together and allowed teams to share their findings as well as providing an opportunity for the cross-pollination of ideas, approaches, and research methodologies.

Key themes

The Hub's research is organised across three key themes, aligning our work with the development and growth of the emerging Quantum Information Technology sector. These themes and their intersections across our research can be seen in Figure 1.

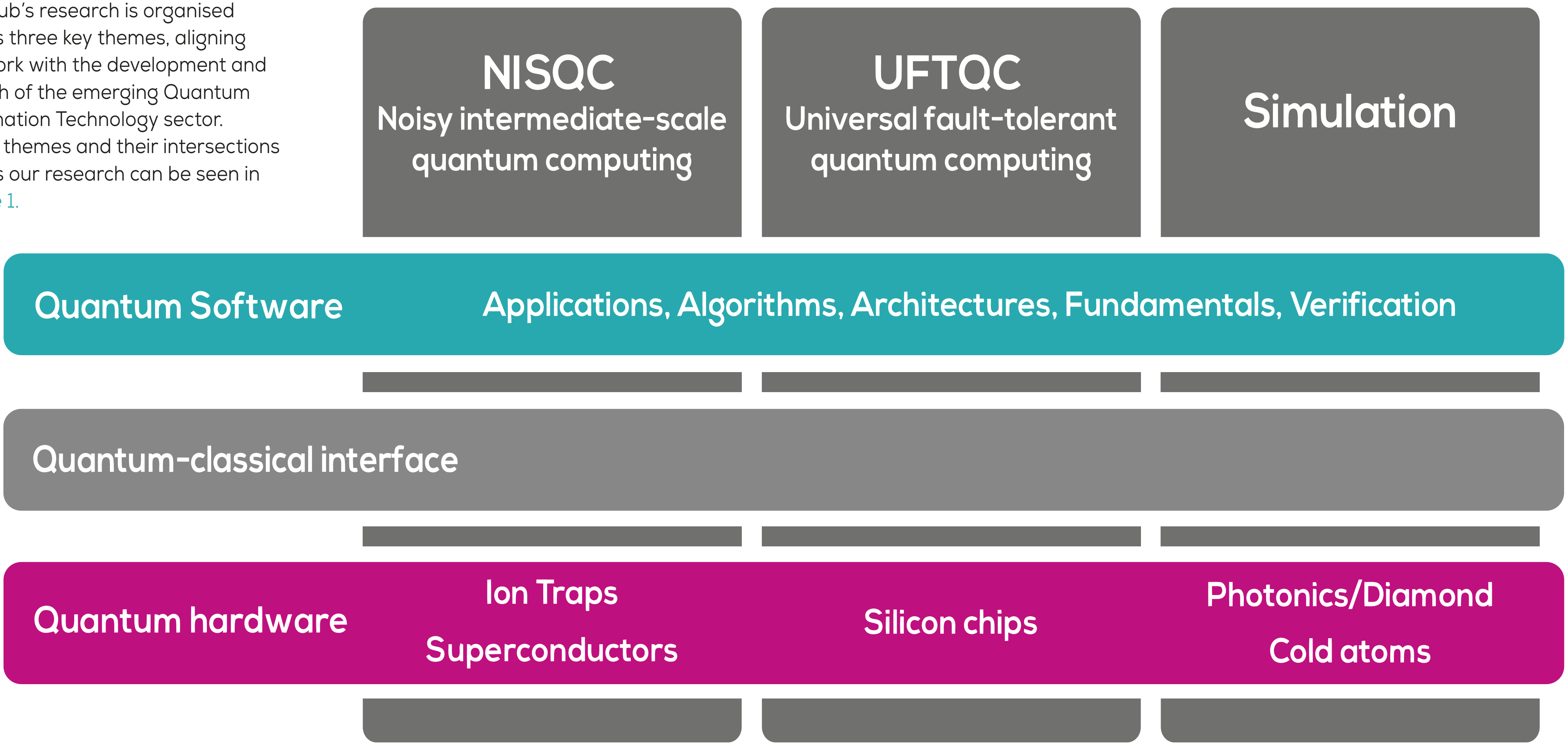


Figure 1: Key themes and research areas within the Hub

Noisy Intermediate-Scale Quantum Computing (NISQC) offers the opportunity to deliver applications in areas such as optimisation tasks and quantum-enhanced machine learning. One of the Hub's key aims in this area has been to develop and prototype industrially or scientifically relevant applications.

The long-term goal of **Universal Fault-Tolerant Quantum Computing** (UFTQC) will ultimately rely on fault-tolerant hardware and software delivered at scale. The Hub has been working on driving forward quantum logic performance (fidelity and speed), and developing techniques across our hardware platforms for scaling to large numbers of qubits and gates.

Our **Simulation** theme has focused on the development of technologies that use quantum systems to model complex natural processes which are out of the reach of classical digital computers. Quantum simulators can provide viable near-term solutions for high-value applications in fields such as logistics, materials discovery, and chemistry.

Every year the Hub has been able to share our research with a wider audience as an exhibitor at the National Quantum Technologies Showcase event in London. This annual event, which started in 2015, brings together the UK's quantum community to highlight developments, not just in quantum computing but across the full spectrum of quantum technologies.

Studentships

The Hub has received an annual allocation of EPSRC-funded doctoral training programme studentships which have been allocated through a competitive call open to Hub academics and partner institutions. Specific efforts are made to consider equality and ensure that the recruitment processes for the successful research themes are available to as diverse a pool of candidates as possible. At any one time the Hub has typically supported between 30 and 40 students. These students have contributed strongly to the quantum community, regularly presented at Hub events, and frequently moved on to research positions within the QC research community or spin-out companies.

Career development

The Hub has supported its Early Career Researchers (ECRs) with several initiatives. Training activities have covered topics from entrepreneurship to applying for funding, and alongside these we have run a "Researcher Day" event that included a diverse range of speakers from academic and industrial partners talking about how their careers had progressed and how researchers might consider developing their own careers in quantum computing. We have encouraged ECRs to apply for our partnership resource grants in collaboration with a more senior investigator, and many of our successful applications have resulted from this approach.

We have also supported several Fellowship applications and have added two early career researchers (ECRs) as Hub investigators.

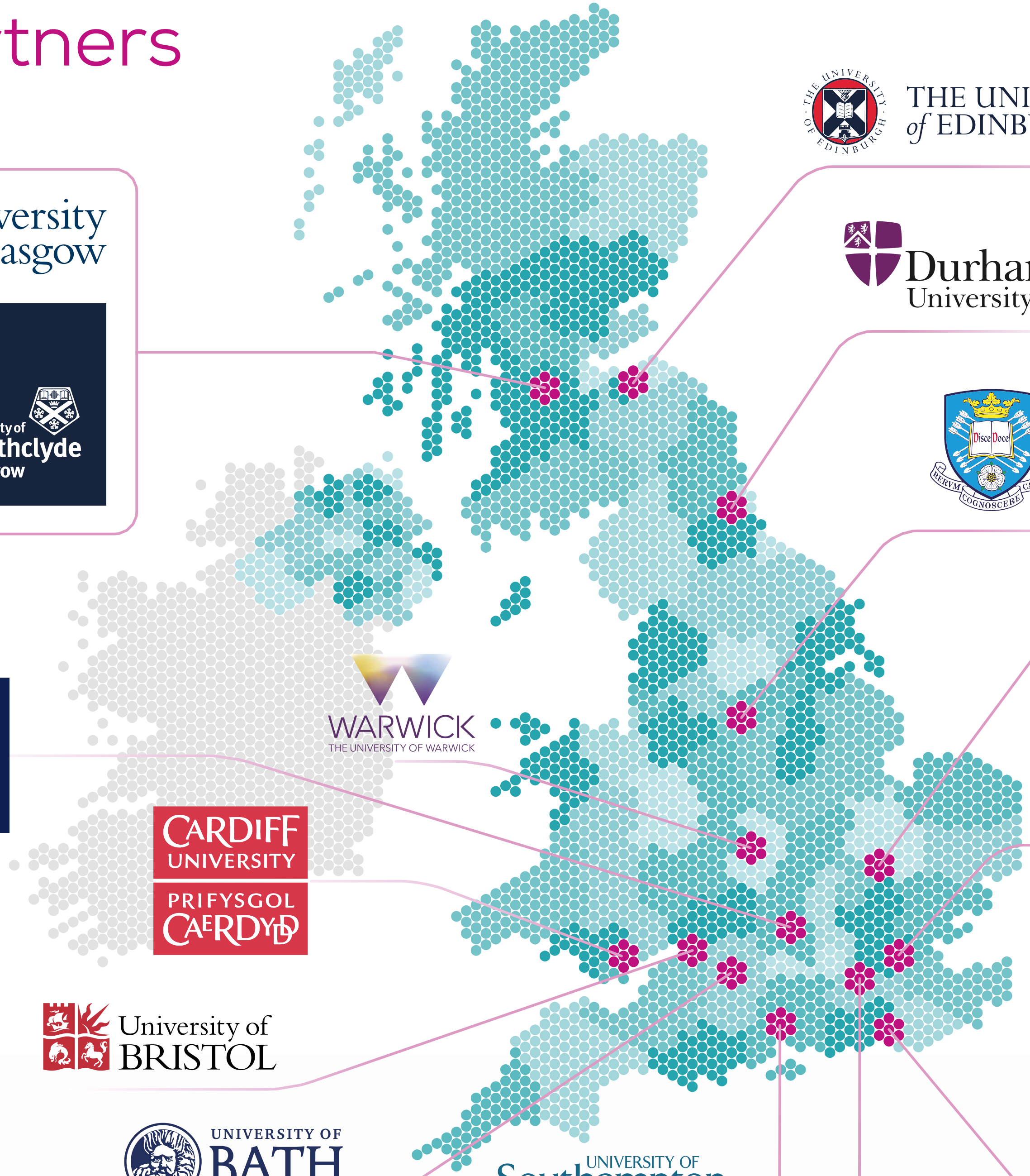
In 2024 the Hub held a Researcher Retreat near Oxford, organised by ECRs. This two-day event for students and ECRs, was designed to pool expertise, share knowledge, and build networks across different fields. With around 30 attendees, the event focussed on both theoretical and experimental disciplines, including presentations on the state-of-the-art in each area, frontier talks, and interactive sessions. Guest speakers, including Zhanet Zaharieva, Co-Founder & COO of Quantum Dice, and Jonathan Legh-Smith, Executive Director of UKQuantum, provided insights into taking research from the lab into the real world, and an overview of the developing quantum landscape outside of academia.

Supporting the Hub's research efforts

A small team, based in Oxford, provides support for the Hub's research activities. Our Senior Programme Manager, Chris Skinner, is responsible for the management of Hub resources, financial oversight and reporting, and provides other assistance to the directors. Our Programme Support Officer, Nasreen Al-Hamdani, provides general management of administrative office activities and supports the Programme Manager and directors. Adi Sheward-Himpson is the Hub's Communications Manager, responsible for the development and implementation of our communications strategy.

The Hub has a User Engagement (UE) team, led by Chris Noble, with Technology Associate Keith Norman. This team is responsible for engaging with the quantum community beyond academia, understanding the wider quantum computing landscape, and building relationships in key industrial and commercial sectors.

Hub Partners



Our Team

Leadership Team

Professor Dominic O'Brien

QCS Hub Director

Dominic O'Brien has two decades of experience in photonic systems integration, including system design, integration process development, and control system development, resulting in world-leading optical wireless system performance. He has worked extensively with international academic and industrial partners, with ~300 publications and patents in this area. He was previously Co-Director for Systems Engineering in the Networked Quantum Information Technologies Hub (NQIT), and is Director of the EPSRC-funded Hub in All-Spectrum Connectivity.

Professor David Lucas

Principal Investigator

David Lucas has a wide range of expertise in experimental quantum physics, including precision measurements, cold atoms, and trapped ions. He is co-leader of the Oxford University ion trap quantum computing research group which has realised a full set of one- and two-qubit operations with world-leading performance far surpassing fault-tolerance thresholds. He also leads Oxford's participation in several European and US projects - including the management committee of the EU COST IOTA, primarily an experimental group testing and developing ideas in quantum computing using laser-manipulated trapped ions. He is also involved in theoretical activity, concerned mainly with quantum fault-tolerant methods and quantum error correction.

Christopher Noble

Co-Director for User Engagement

Chris Noble is a Chartered Engineer, with a background in advanced manufacturing and emerging technologies. He has years of experience in both business development and in leading technology adoption, and is a named inventor on several patents. As an ED&I Fellow at the University of Oxford, he is committed to supporting and advancing diversity and inclusion at the Hub.

Senior science team

In addition to his role as Principal Investigator, Professor David Lucas is joined on our senior science team by:

Professor Ian Walmsley

Ian Walmsley is Provost of Imperial College London, and Chair in Experimental Physics. His research in optical science and technology ranges from ultrafast optics to quantum information science and he has pioneered quantum photonics for sensing, communication, and simulation. He is a Fellow of the Royal Society, Optica, the American Physical Society, and the Institute of Physics. He was the Director of the Networked Quantum Information Technologies Hub (NQIT). In 2024 he was awarded a CBE for services to science and quantum technologies.

Professor Elham Kashefi

Elham Kashefi is Professor of Quantum Computing at the University of Edinburgh, CNRS Director of Research at Sorbonne Université and Chief Scientist for the UK National Quantum Computing Centre. She has pioneered transdisciplinary research on the structure, behaviour, and interactions of quantum technology, from formal and foundational aspects to industrial use-case delivery. Her research team innovates across a broad range of platforms, with an integrated software research programme delivering impact in quantum computing and quantum networks. She has received EPSRC Early Career and Established Career Fellowship awards, is a recipient of the Les Margaret Entrepreneur prize, and an elected fellow of the Royal Society of Edinburgh. She co-authored the EU Quantum Software Manifesto, was an Associate Director in the NQIT Hub, and is co-founder and director of the Quantum Software Lab at Edinburgh.

Management board

The Management Board of the Hub, chaired by the Hub Director, meets quarterly to review progress against agreed technical milestones, budget, and other operational aspects. They monitor progress, identify risks, and agree on actions as required. The Board also oversee ED&I, consider programme risks, and agree budgets and changes to the work programme as well as allocating funding for collaborative projects and strategic partnerships.

Professor Dominic O'Brien

Professor David Lucas

Christopher Noble

Professor Ian Walmsley

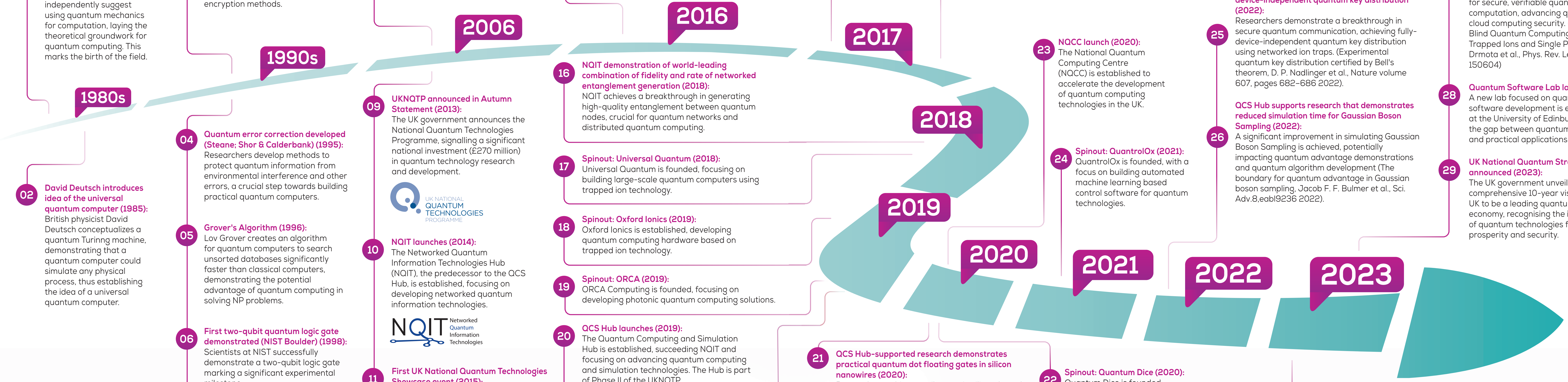
Professor Elham Kashefi

Professor John Morton

Professor Simon Benjamin

Professor Noah Linden

Timeline



01 **Benioff & Feynman propose quantum computing (1980-):**
Physicists Richard Feynman and Paul Benioff independently suggest using quantum mechanics for computation, laying the theoretical groundwork for quantum computing. This marks the birth of the field.

02 **David Deutsch introduces idea of the universal quantum computer (1985):**
British physicist David Deutsch conceptualizes a quantum Turinng machine, demonstrating that a quantum computer could simulate any physical process, thus establishing the idea of a universal quantum computer.

03 **Shor's Algorithm (1994):**
Peter Shor develops an algorithm for quantum computers to efficiently factor large numbers, potentially breaking widely-used encryption methods.

04 **Quantum error correction developed (Steane; Shor & Calderbank) (1995):**
Researchers develop methods to protect quantum information from environmental interference and other errors, a crucial step towards building practical quantum computers.

05 **Grover's Algorithm (1996):**
Lov Grover creates an algorithm for quantum computers to search unsorted databases significantly faster than classical computers, demonstrating the potential advantage of quantum computing in solving NP problems.

06 **First two-qubit quantum logic gate demonstrated (NIST Boulder) (1998):**
Scientists at NIST successfully demonstrate a two-qubit logic gate marking a significant experimental milestone.

07 **First superconducting qubit (1999):**
Researchers create the first qubit that uses superconducting circuits to hold quantum states.

08 **Ion Trap in Semiconductor Chip (2006):**
Scientists demonstrate an ion trap fabricated on a semiconductor chip, combining the precision of trapped ions with the scalability of semiconductor manufacturing.

09 **UKNQTP announced in Autumn Statement (2013):**
The UK government announces the National Quantum Technologies Programme, signalling a significant national investment (£270 million) in quantum technology research and development.

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10 **NQIT launches (2014):**
The Networked Quantum Information Technologies Hub (NQIT), the predecessor to the QCS Hub, is established, focusing on developing networked quantum information technologies.

NQIT
Networked
Quantum
Information
Technologies

11 **First UK National Quantum Technologies Showcase event (2015):**
The UK hosts its first National Quantum Technologies Showcase, highlighting advancements and potential applications of quantum technologies, both within the quantum community and to to a wider audience.

12 **NQIT demonstrates deterministic placement of high-quality qubits in diamond (2016):**
Researchers achieve precise placement of qubits in diamond using a laser technique, advancing the development, and showing the potential of diamond-based quantum technologies.

13 **NQIT-supported development of unique superconducting qubit architecture (2017):**
NQIT supports the development of a novel superconducting qubit design, contributing to advances in this promising quantum computing platform (Double-sided coaxial circuit QED with out-of-plane wiring, J. Rahamim, et al., Appl. Phys. Lett. 110, 222602 2017).

14 **Spinout: Oxford Quantum Circuits (2017):**
Oxford Quantum Circuits is founded, focusing on developing superconducting quantum computers for commercial applications.

15 **Spinout: Quantum Motion (2017):**
Quantum Motion is established, aiming to create scalable quantum computers using silicon-based technology.

16 **NQIT demonstration of world-leading combination of fidelity and rate of networked entanglement generation (2018):**
NQIT achieves a breakthrough in generating high-quality entanglement between quantum nodes, crucial for quantum networks and distributed quantum computing.

17 **Spinout: Universal Quantum (2018):**
Universal Quantum is founded, focusing on building large-scale quantum computers using trapped ion technology.

18 **Spinout: Oxford Ionics (2019):**
Oxford Ionics is established, developing quantum computing hardware based on trapped ion technology.

19 **Spinout: ORCA (2019):**
ORCA Computing is founded, focusing on developing photonic quantum computing solutions.

20 **QCS Hub launches (2019):**
The Quantum Computing and Simulation Hub is established, succeeding NQIT and focusing on advancing quantum computing and simulation technologies. The Hub is part of Phase II of the UKNQTP.

Quantum
Computing &
Simulation Hub

21 **QCS Hub-supported research demonstrates practical quantum dot floating gates in silicon nanowires (2020):**
Researchers achieve a milestone in silicon-based quantum computing, demonstrating practical quantum dot floating gates in silicon nanowires. (Remote Capacitive Sensing in Two-Dimensional Quantum-Dot Arrays, Jingyu Duan et al., Nano Lett. 2020, 20, 10, 7123–7128)

22 **Spinout: Quantum Dice (2020):**
Quantum Dice is founded, developing a self-certifying quantum random number generating device that uses light to create completely unpredictable, unrepeatable encryption keys.

23 **NQCC launch (2020):**
The National Quantum Computing Centre (NQCC) is established to accelerate the development of quantum computing technologies in the UK.

24 **Spinout: QuantrolOx (2021):**
QuantrolOx is founded, with a focus on building automated machine learning based control software for quantum technologies.

25 **QCS achieves first demonstration of fully-device-independent quantum key distribution (2022):**
Researchers demonstrate a breakthrough in secure quantum communication, achieving fully-device-independent quantum key distribution using networked ion traps. (Experimental quantum key distribution certified by Bell's theorem, D. P. Nadlinger et al., Nature volume 607, pages 682–686 2022).

26 **QCS Hub supports research that demonstrates reduced simulation time for Gaussian Boson Sampling (2022):**
A significant improvement in simulating Gaussian Boson Sampling is achieved, potentially impacting quantum advantage demonstrations and quantum algorithm development (The boundary for quantum advantage in Gaussian boson sampling, Jacob F. F. Bulmer et al., Sci. Adv.8,eabl9236 2022).

27 **QCS Hub demonstrates verifiable blind quantum computing with trapped ions and single photons (2023):**
Researchers showcase a method for secure, verifiable quantum computation, advancing quantum cloud computing security. (Verifiable Blind Quantum Computing with Trapped Ions and Single Photons, P. Drmota et al., Phys. Rev. Lett. 132, 150604)

28 **Quantum Software Lab launch (2023):**
A new lab focused on quantum software development is established at the University of Edinburgh, bridging the gap between quantum hardware and practical applications.

29 **UK National Quantum Strategy announced (2023):**
The UK government unveils a comprehensive 10-year vision for the UK to be a leading quantum-enabled economy, recognising the importance of quantum technologies for the UK's prosperity and security.

30 **Quantum Missions Announced (2023):**
The UK announces specific quantum technology missions, including the aim that "by 2035, there will be accessible, UK-based quantum computers capable of running 1 trillion operations and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy."

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

The UK's National Quantum Technologies Programme (NQTP) was established in 2014, with the creation of four Quantum Research Hubs. These Hubs were in: Communications, led by the University of York; Sensors and Timing, led by the University of Birmingham; Enhanced Imaging, led by the University of Glasgow; and Computing, led by the University of Oxford. The Hubs were initially funded for a period of five years, before being refreshed in 2019 for a second phase of a further five years. The Government has provided £214m in funding over this period to the Hubs, which now span over 30 research institutions across the UK.

Alongside this, the Programme is supported by endeavours to drive commercialisation and industrial involvement. Notable is the Industrial Strategy Challenge Fund (ISCF). This has been delivered in waves to provide £153m to businesses that in-turn have gone on to raise £425 million in private sector financing. A directory of the ISCF-funded projects is available at https://www.ukri.org/publications/project-directory-for-the-uk-quantum-technologies-challenge/.

National capabilities have been established, firstly with the creation of the National Physical Laboratory's (NPL) Quantum Metrology Institute in 2015 - a national capability for test and evaluation, which aims to accelerate the commercialisation of quantum technologies. More recently a new national lab based at the Harwell Campus in Oxfordshire, the National Quantum Computing Centre (NQCC), has been established as part of the NQTP's second phase. In 2024 the NQCC announced an award of £30m to seven UK quantum technology companies – Aegiq, Cold Quanta UK, ORCA Computing, Oxford Ionics, Quantum Motion, QuEra Computing and Rigetti UK – to develop, build and ultimately deploy operationally ready quantum computing testbeds at the NQCC. Part of the national capability is also delivered by the Hartree National Centre for Digital Innovation, a collaborative programme with IBM which will enable businesses to acquire the skills required to adopt digital and emergent technologies, including quantum computing.

Supporting this effort is the Quantum Software Lab, launched at the University of Edinburgh in 2023 as part of a strategic partnership with the NQCC. It aims to act as the central hub for quantum software development in the UK whilst collaborating with hardware developers and end-users across government, academia, and industry.

Underpinning the national programme has been a strong investment in skills, with studentship support, fellowships, the establishment of three Training and Skills Hubs in Quantum Systems Engineering, and five new Centres for Doctoral Training in Quantum Technologies announced in March 2024. A coordinated NQTP outreach effort has been delivered through Quantum City (https://www.quantumcity.org.uk), which seeks to raise the profile of quantum technologies amongst the public and schools to build the future quantum workforce and facilitate discussions about the role of these technologies in society.

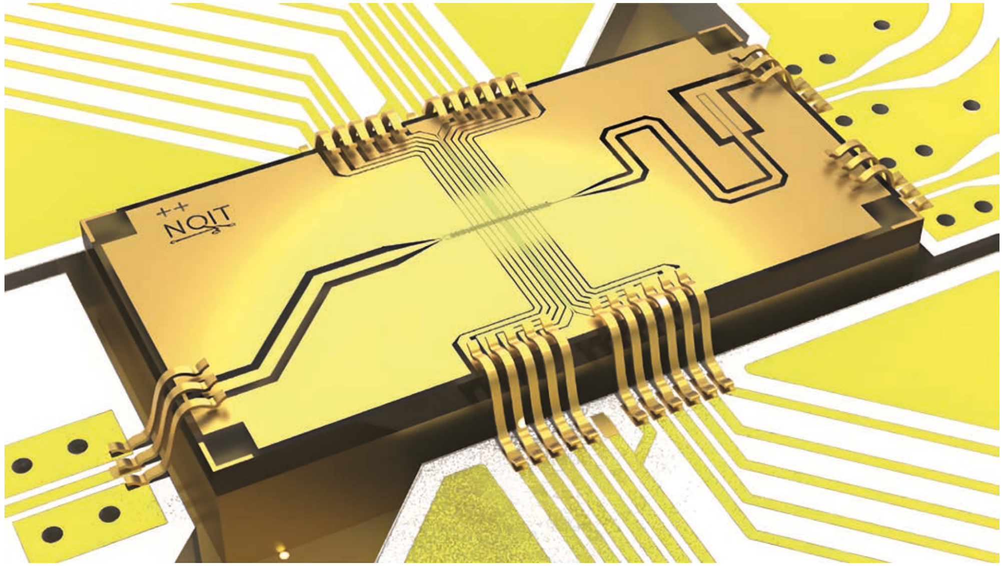
International partnerships have been a key element of the UK's success over the first ten years of the National Programme, with bilateral agreements including quantum technologies between the UK and the USA, Canada, Australia, Germany and the Netherlands. In the summer of 2023, the four UK Quantum Technology Hubs organised an International Summer School in Quantum Technologies, bringing together 60 of the most promising postgraduate student researchers from the quantum communities of the UK and Canada.

Quantum Computing Hubs

The Networked Quantum Information Technologies Hub (NQIT) ran from 2014 to 2019, bringing together nine academic partners from across the UK, and supported by 23 industrial partners. NQIT was divided into Hardware, Applications and Architecture programmes, alongside Engagement and Responsible Research and Innovation activities.

NQIT's work on solid-state devices, led in 2016 to the first ever utilisation of laser writing to generate nitrogen-vacancy (NV) centres in diamond, whilst avoiding damage to the crystal lattice associated with other methods [1]. This enabled the optical addressing of arrays of identical solid-state qubits.

A central theme of NQIT's research was the optical networking of trapped-ion qubits by linking together ion trap modules using single photons of light in optical fibres. The techniques are a promising method for distributed computing and modular scaling, and also have applications in quantum communications and metrology. In 2018, NQIT supported the development of a two-node network which demonstrated a world-leading combination of fidelity and rate of remote entanglement generation [2].



Chip trap developed at Oxford University for high-speed, highfidelity microwave-driven quantum logic operations. [Jochen Wolf]

2019 saw the introduction of QuEST – the Quantum Exact Simulation Toolkit – a standalone, high-performance simulator of quantum circuits, state vectors, and density matrices, with simple code that could run on multiple platforms, from a laptop to a supercomputer. The associated whitepaper [3] was Scientific Reports' 11th most downloaded Physics paper of 2019.

Building on the achievements of NQIT, the Quantum Computing & Simulation Hub was established in December 2019, with a consortium of 17 universities and 43 co-investigators, and supported by 27 industrial partners. The QCS Hub consists of 11 work packages, covering the full quantum computing stack: software, verification, and benchmarking, alongside the major quantum computing architectures of ion traps, superconducting circuits, diamond, silicon, photonics, and cold atoms.

In 2020, using a floating metal gate that connects two separate nanowires, QCS Hub researchers developed a way to scale the coupling between qubits in silicon nanowires in 2D. This enabled a quantum dot in one nanowire to sense the state of a quantum dot in another, opening a potential route to 2D scaling of quantum dot arrays across nanowires [4].

In 2023 a collaboration between the Hub's hardware and software researchers led to the demonstration of verifiable blind quantum computing, with significant implications for privacy and security improvements in cloud-based quantum systems [5].

References

[1] Chen, Y. e. (2017). Laser writing of coherent colour centres in diamond. Nature Photonics, 77–80(11).

[2] Drmota, P. e. (2023). Verifiable blind quantum computing with trapped ions and single photons. arXiv, 2305.02936.

[3] Duan, J. e. (2020). Remote Capacitive Sensing in Two-Dimensional Quantum-Dot Arrays. Nano Lett, 20(10), 7123-7128.

[4] Jones, T. e. (2019). QuEST and High Performance Simulation of Quantum Computers. Scientific Reports, 9(10736).

[5] Stephenson, L. J. (2020). High-Rate, High-Fidelity Entanglement of Qubits Across an Elementary Quantum Network. Physical Review Letters, 124(110501).

Hardware research at the Hub

The Hub’s research is broken into two distinct categories: hardware, and software and applications. Six of our work packages focus on developing the hardware required to turn quantum computing into a practical everyday tool and ion traps, superconductors, diamond chips, photonics, silicon quantum processors, and cold atoms are discussed over the following pages.

The Hub’s photonics research takes place at the universities of Bristol, Bath, and Cardiff, and at Imperial College, London. Here we see students Ed Deacon and Imogen Forbes working in the lab at the University of Bristol.

Ion Traps

Research Lead

Professor David Lucas

University of Oxford

David Lucas has a wide range of expertise in experimental quantum physics, including precision measurements, cold atoms, and trapped ions. He is Co-Leader of the Oxford University ion trap quantum computing research group which has realised a full set of one- and two-qubit operations with world-leading performance far surpassing fault-tolerance thresholds. He also leads Oxford's participation in several European and US projects - including the management committee of the EU COST IOTA, primarily an experimental group testing and developing ideas in quantum computing using laser-manipulated trapped ions. They are also involved in theoretical activity, concerned mainly with quantum fault-tolerant methods and quantum error correction.

Introduction

Trapped atomic ions are the most mature qubit platform, benefitting from more than two decades of research and development since the first entangling logic gates were demonstrated in the late 1990s. They are pursued worldwide in universities, national labs, and industrial settings.

The Hub's work on ion traps focuses on using individual atomic ions trapped in microfabricated chip traps. Trapped ions constitute atomically perfect identical qubits, and can be manipulated with laser beams or microwave electronics to make elementary quantum logic gates of the highest possible precision. It is however recognised that the long-term goal of universal fault-tolerant quantum computing will require both higher logic gate fidelities than the present state-of-the-art (around 99.9%) and methods of scaling up to large numbers of qubits, in particular via quantum networking. The Hub's ion trap research addressed both of these challenges.

Our ion trap work is led from Oxford, and involves co-investigators at Imperial College, London, Southampton, and Sussex universities.

Quantum networking

A central theme of the research is the optical networking of trapped-ion qubits by linking together trap modules using single photons of light in optical fibres. As well as being a promising method for distributed computing and modular scaling, the techniques have applications in quantum communications and metrology.

The two-node network which was constructed in the Phase 1 NQIT Hub exhibited a world-leading combination of fidelity and rate of remote entanglement generation, across all physical platforms, and still sets the state-of-the-art [1]. We used this system to produce the first full example of a "device-independent" quantum key distribution protocol, where the security was derived from the use of entangled qubits with minimal assumptions about the behaviour of the physical apparatus [2].

We also made the first demonstration of "entangled atomic clocks", enabling an improvement in the precision of clock frequency comparison close to the Heisenberg Limit (the ultimate limit allowed by quantum mechanics) [3]. More recently, we have shown that our mixed-species logic gates can be used to couple an interface qubit to a memory qubit, extending the memory coherence time in a network node to around 10 seconds [4], and used this new capability to present verifiable "blind" quantum computing for the first time [5].

Optical cavities

The integration of optical cavity technology with ion traps will enable a step-change in the efficiency of ion-photon coupling, which could in turn boost networked entanglement rates towards MHz speeds. It can also give access to infra-red photons suitable for longer-distance optical fibre links.

We showed enhanced ion-cavity coupling using cavity cooling techniques [6] and also theoretically studied the use of non-spherical cavity mirrors showing that this can enhance the atom/cavity coupling [7] and the modelling of mode mixing effects [8]. We developed fabrication techniques to enable the precise integration of miniature optical cavities with microfabricated ion traps, and constructed two ion trap systems with cavities.

Logic gates

We extended our earlier work on high-fidelity laser-driven entangling gates from same-species ions to gates between different atomic elements, with world-leading precision, and performed a comparative benchmarking study of the entangling operation [9]. We proposed methods for making microwave-driven gates more robust to typical noise sources [10] and also investigated methods for diagnosing motional coherence (on which ion trap quantum logic operations usually depend) [11]. We demonstrated the first entangling gate using a laser standing wave, which can allow conventional limits on the gate speed to be surpassed, and applied it to "omg" qubits [12].

Chip trap development

A cryogenic system based around a microfabricated chip trap was constructed to increase the speed of microwave-driven gates [13]. We used this system to demonstrate new world records for microwave-driven ("laser-free") gates: the highest-fidelity addressed single-qubit gates [14] and the fastest two-qubit gates in the high-fidelity (>99%) regime [15]. We constructed a dual chip-trap system as a demonstrator for beyond-single-chip scalability, and shuttled an ion-qubit back and forth between the chips at high speed (<1ms), achieving millions of transfers without ion loss [16].

Ion trap partnership projects

The core activity of our ion trap work has been supplemented by several Partnership Resource Fund (PRF) projects. Two such projects are"CaQTUS" (with Oxford Ionics Ltd) to create a quick-turnaround system for testing chip traps, and"SQUARE" which developed a photonic waveguide chip for laser-addressing an array of ions in a single trap [17]. The Quantum Communications Hub also provided PRF funding to investigate increasing the range of the device-independent QKD demonstration to longer fibre links.

Future directions

The unique quantum networking system that we have built up, where a fast, high-fidelity optical link connects processor nodes with excellent memory and local logic gates, will allow the first demonstrations of true "distributed" quantum algorithms involving qubits in different nodes. Our optical cavity demonstrators hold the promise of greatly boosting the speed of optical links, and potentially interfacing to different qubit types. The microwave-driven chip trap operations have shown that electronics methods for quantum logic can compete with more conventional laser-based methods; the next steps are to extend this to larger registers of qubits. Chip trap developments, incorporating integrated optics, promise simpler and more reliable ion trap processors.

References

[1] L.J.Stephenson, D.P.Nadlinger et al., Phys.Rev.Lett. **124** 110501 (2020).

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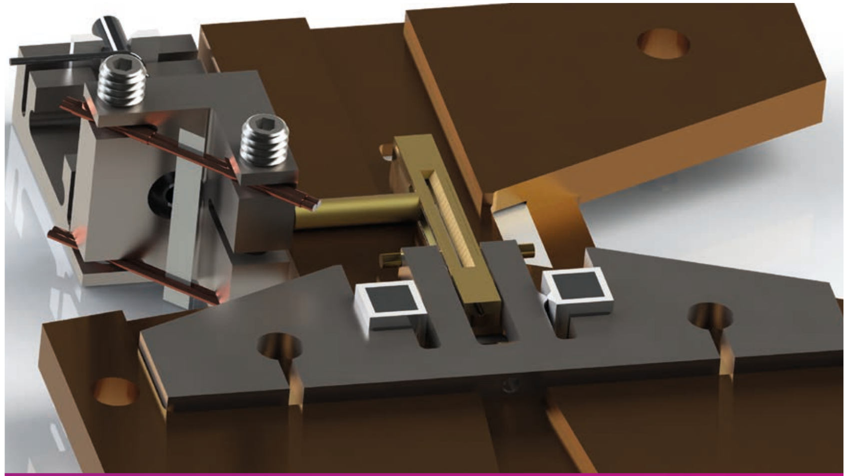
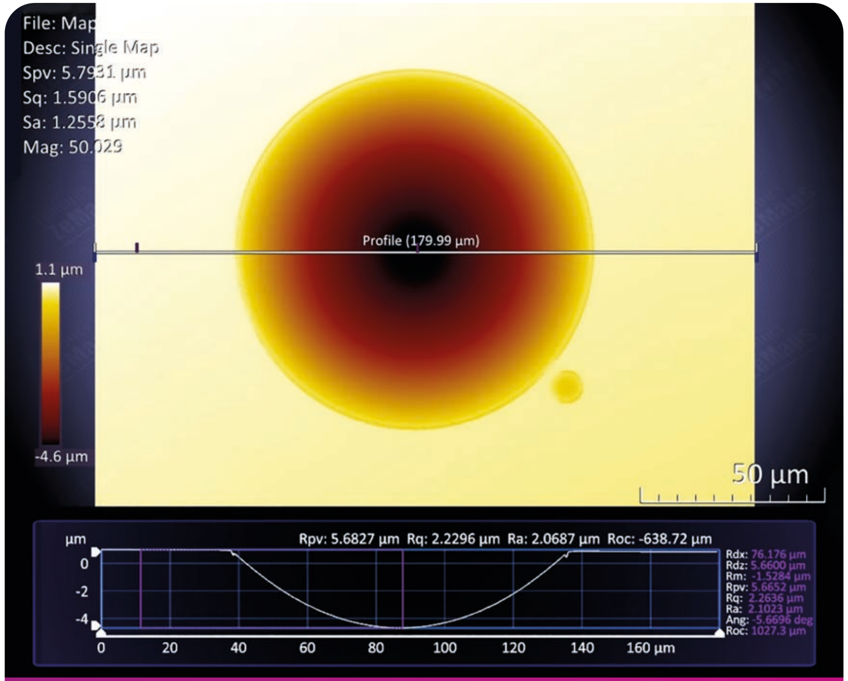


Combined chip trap and optical cavity system under construction at Sussex University. [Matthias Keller]



File: Map
Desc: Single Map
Spv: 5.7931 µm
Sq: 1.5906 µm
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Rpv: 5.6827 µm Rq: 2.2296 µm Ra: 2.0687 µm Roc: -638.72 µm

Rdx: 76.176 µm
Rdz: 5.6600 µm
Rm: -1.5284 µm
Rpv: 5.6652 µm
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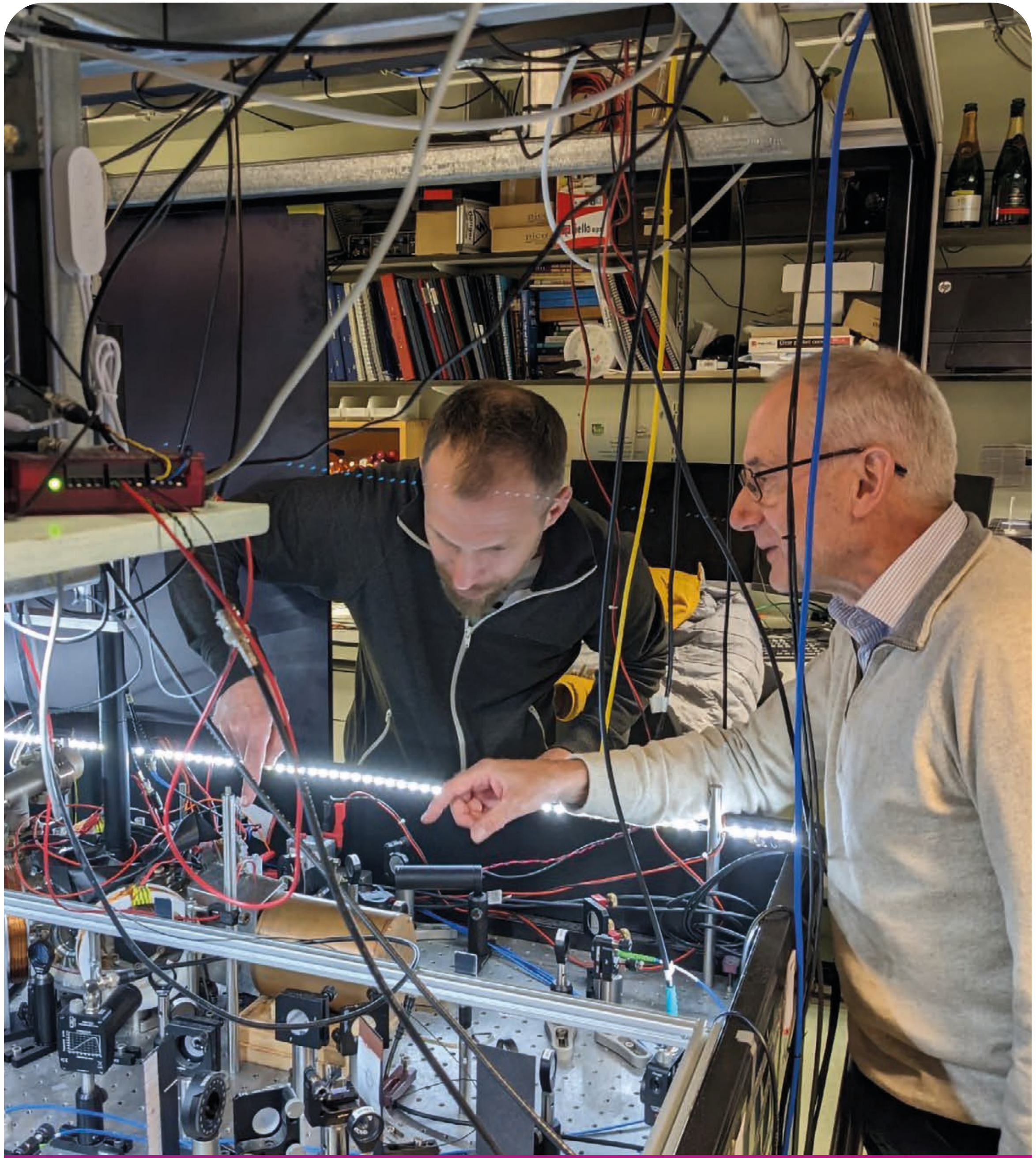
Surface profiling of prototype cavity mirrors at the University of Southampton. [James Gates]



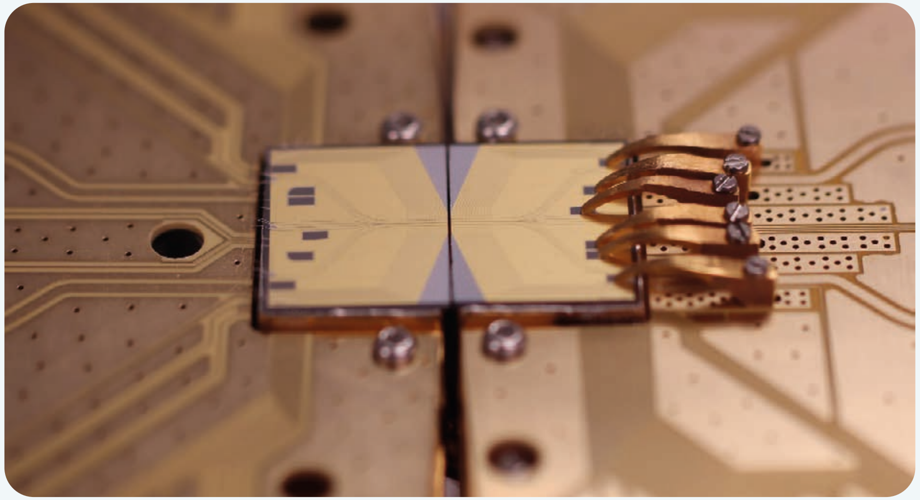
Florian Mintert and Richard Thompson in the lab at Imperial College, London.

Featured Paper

A high-fidelity quantum matter-link between ion-trap microchip modules

M. Akhtar, F. Bonus, F. R. Lebrun-Gallagher, N. I. Johnson, M. Siegele-Brown, S. Hong, S. J. Hile, S. A. Kulmiya, S. Weidt, W. K. Hensinger, Nature Communications 14 531 (2023).

System scalability is fundamental for large-scale quantum computers (QCs) and is being pursued over a variety of hardware platforms. For QCs based on trapped ions, architectures such as the quantum charge-coupled device (QCCD) are used to scale the number of qubits on a single device. However, the number of ions that can be hosted on a single quantum computing module is limited by the size of the chip being used. Therefore, a modular approach is of critical importance and requires quantum connections between individual modules. Here, we present the demonstration of a quantum matter-link in which ion qubits are transferred between adjacent QC modules. Ion transport between adjacent modules is realised at a rate of $2424 s^{-1}$ and with an infidelity associated with ion loss during transport below 7×10^{-8}. Furthermore, we show that the link does not measurably impact the phase coherence of the qubit. The quantum matter-link constitutes a practical mechanism for the interconnection of QCCD devices. Our work will facilitate the implementation of modular QCs capable of fault-tolerant utility-scale quantum computation.



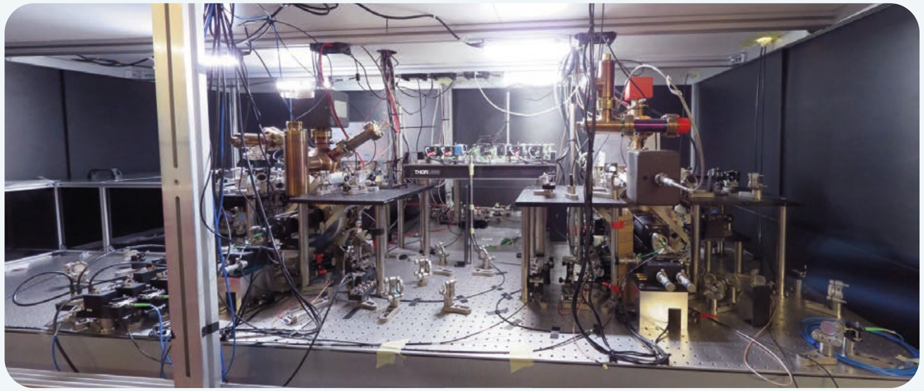
Twin ion chip trap setup at Sussex University, used to demonstrate shuttling of ion-qubits between different chips. [Winfried Hensinger]

Featured Paper

A quantum network of entangled optical atomic clocks

B. C. Nichol, R. Srinivas, D. P. Nadlinger, P. Drmota, D. Main, G. Araneda, C. J. Ballance, D. M. Lucas, Nature 609 689 (2022).

Optical atomic clocks are our most precise tools to measure time and frequency. They enable precision frequency comparisons between atoms in separate locations to probe the space-time variation of fundamental constants, the properties of dark matter, and for geodesy. Measurements on independent systems are limited by the standard quantum limit (SQL); measurements on entangled systems, in contrast, can surpass the SQL to reach the ultimate precision allowed by quantum theory - the so-called Heisenberg limit. While local entangling operations have been used to demonstrate this enhancement at microscopic distances, frequency comparisons between remote atomic clocks require rapid high-fidelity entanglement between separate systems that have no intrinsic interactions. We demonstrate the first quantum network of entangled optical clocks using two 88Sr+ ions separated by a macroscopic distance (2m), that are entangled using a photonic link. We characterise the entanglement enhancement for frequency comparisons between the ions. We find that entanglement reduces the measurement uncertainty by a factor close to $\sqrt{2}$, as predicted for the Heisenberg limit, thus halving the number of measurements required to reach a given precision. Our results show that quantum networks have now attained sufficient maturity for enhanced metrology. This two-node network could be extended to additional nodes, to other species of trapped particles, or to larger entangled systems via local operations.



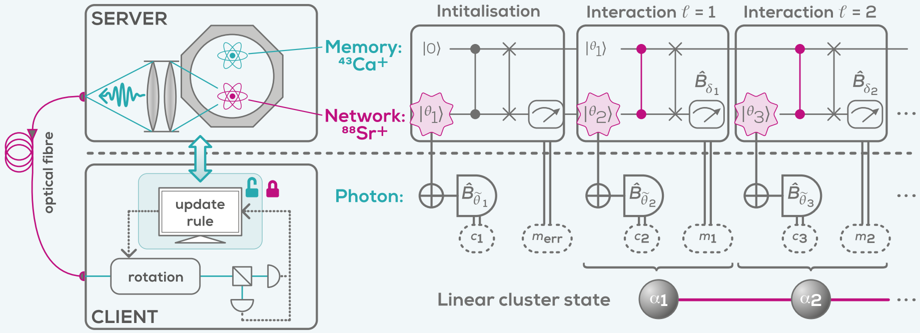
Quantum network lab showing dual ion trap setup used for the "entangled clocks" experiment [Oxford University].

Featured Paper

Verifiable blind quantum computing with trapped ions and single photons

P. Drmota, D. P. Nadlinger, D. Main, B. C. Nichol, E. M. Ainley, D. Leichtle, A. Mantri, E. Kashefi, R. Srinivas, G. Araneda, C. J. Ballance, D. M. Lucas, Phys. Rev. Lett. (in press, 2024).

We have made the first scalable demonstration of verifiable and blind quantum computation (BQC), using a hybrid architecture of trapped-ion and photonic qubits. BQC can offer unbreakable security for cloud-based quantum computing, where quantum "servers" can process quantum information "blindly", i.e., without access to the information being processed for the "client". We present the first experimental implementation of a deterministic (and therefore scalable), BQC protocol. Furthermore, it also features built-in "verification", i.e., the ability to determine whether the computation is performed correctly. Our results show for the first time that verifiable BQC in the cloud is resource-efficient and practical. This has enormous implications in areas where sensitive or confidential information is processed. While theoretical proposals have been numerous, previous experimental attempts have been limited to proof-of-principle examples on purely photonic platforms, which suffer from a number of fundamental limitations, such as the lack of quantum memory, and are inherently not scalable. Our implementation leverages a unique experimental setup that integrates a state-of-the-art matter-to-photon qubit interface with a long-lived qubit memory and deterministic quantum logic. We combine this with a novel system of fast and adaptive hardware to facilitate true shot-by-shot randomisation of all protocol parameters. These capabilities represent step-change advances compared to previous approaches as they enable the scalability and security of the implementation. The results demonstrate that trapped ions – already renowned as one of the leading quantum computing platforms – can also provide ultimate security for quantum computing in the cloud through BQC.



Protocol used for demonstration of verifiable blind QC, using a trapped-ion quantum "server" and a photonic "client".

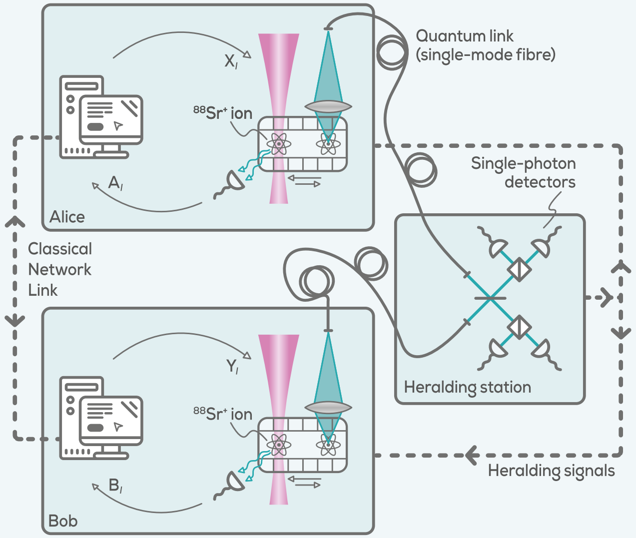
Featured Paper

Experimental quantum key distribution certified by Bell's theorem

D. P. Nadlinger, P. Drmota, B. C. Nichol, G. Araneda, D. Main, R. Srinivas, D. M. Lucas, C. J. Ballance, K. Ivanov, E. Y-Z. Tan, P. Sekatski, R. L. Urbanke, R. Renner, N. Sangouard, J-D. Bancal, Nature 607 - 682 (2022).

Cryptographic key exchange protocols traditionally rely on computational conjectures such as the hardness of prime factorisation to provide security against eavesdropping attacks. Remarkably, quantum key distribution protocols like the one proposed by Bennett and Brassard provide information-theoretic security against such attacks, a much stronger form of security unreachable by classical means. However, quantum protocols realised so far are subject to a new class of attacks exploiting implementation defects in the physical devices involved, as demonstrated in numerous ingenious experiments. Following the pioneering work of Ekert, proposing the use of entanglement to bound an adversary's information from Bell's theorem, we realize a complete quantum key distribution protocol immune to these vulnerabilities. We achieve this by combining theoretical developments on finite-statistics analysis, error correction, and privacy amplification, with an event-ready scheme enabling the rapid generation of high-fidelity entanglement between two trapped-ion qubits connected by an optical fibre link. The secrecy of our key is guaranteed device-independently: it is based on the validity of quantum theory, and certified by measurement statistics observed during the experiment. Our result shows that provably secure cryptography with real-world devices is possible, and paves the way for further quantum information applications based on the device-independence principle.

This work was a collaboration of QCS researchers with theorists from Paris/ETH Zurich/ Geneva/Lausanne.



Scheme of the setup for device-independent quantum key distribution.

Superconductors

Research Lead

Dr Peter Leek
University of Oxford

Peter Leek leads the Superconducting Quantum Devices Group in the Oxford University Department of Physics. His group works on designing, understanding, and controlling electrical circuits built from superconductors.

Dr Leek is also the founder of Oxford Quantum Circuits Ltd, an Oxford University spin-out, taking the ideas developed in his group and building on them to develop superconducting-circuit-based quantum computers for real-world applications.

Introduction

Superconducting circuits are a quantum computing hardware platform that is very broadly pursued worldwide both in academia and in industry. The technology has matured to such a level that circuits with hundreds of physical qubits have been demonstrated, but there remain hurdles to overcome to reach high enough performance at a large enough scale for useful quantum computation.

Coordinated research on the use of superconducting circuits as a hardware platform for quantum computing has been carried out in the QCS Hub in the research groups of Peter Leek, Martin Weides, Eran Ginossar, Paul Warburton and Phil Meeson at the Universities of Oxford, Glasgow, Surrey, University College London and Royal Holloway, University of London.

Research focus

Our research has focused on overcoming some of the hurdles facing superconducting circuits in quantum computing, particularly:

(i) The development of fast, high-fidelity two-qubit logic gates
(ii) The analysis and elimination of logic gate errors at scale
(iii) Improving qubit coherence from fabrication
(iv) Improving the functionality of superconducting circuit quantum annealers

High-fidelity logic gates

In our pursuit of high-fidelity logic gates we have been working in Oxford with a patented tileable 3D-integrated circuit design [1]. Early hub research on this topic showed that we could scale this circuit design without suffering from microwave engineering issues that emerge in circuits with large dimensions [2]. We then developed a novel approach to connect the two sides of our circuit enclosures without impacting coherence and were able to demonstrate state-of-the-art performance in a 4-qubit prototype [3].

To develop fast two-qubit logic, we needed to incorporate fast magnetic flux control into our architecture without compromising the excellent microwave performance of the tileable design. We developed a novel approach that uses a 'gradiometric' flux control that minimises flux crosstalk to neighbouring qubits to <1% and enables high bandwidth local control of each qubit in the grid. Combining this gradiometric control with new flux-tuneable qubit designs, we have been able to implement two-qubit logic gates with fidelity >95% in only 75ns and expect significant improvement with parameter refinement.

Gate errors at scale

In our research on gate errors at scale, we have carried out a series of experiments with uncoupled grids of coaxial qubits, showing that we could reach single-qubit gate errors as low as 0.02%, with error correlations remaining undetectable at this level [3]. We were able to quantify the levels of signal crosstalk between circuit elements to be consistent with these errors remaining low as we scale. We extended these findings to a 16-qubit scale, finding similarly promising results.

In theoretical work at the University of Surrey, we developed a theory for robust high-fidelity control of large qubit arrays with fixed couplings [4] which can be incorporated into next-generation experiments. Testing of the single qubit gate pulses on an IBM device showed robustness against control pulse amplitude variations. Additional ongoing work in an I-PRF project also showed robustness against frequency errors.

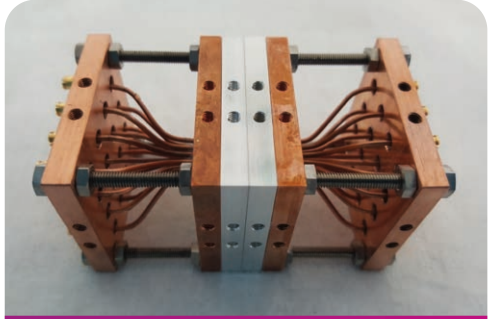


Figure 1. Precision-machined enclosure for 16-qubit superconducting device (University of Oxford)

Figure 2. 16-qubit superconducting device (University of Oxford)

Qubit coherence from fabrication

In our research on qubit coherence from fabrication, we have been able to develop a fabrication process at Oxford that consistently produces qubits with energy relaxation times that compete with some of the best in the world, showing $T_1 \sim 150\mu s$ in a 4-qubit prototype [3]. In work at Glasgow, we have also been able to produce competitive coherence devices with a new robust fabrication approach that promises greater long-term scalability [5]. Improving coherence further hinges on controlling material loss mechanisms, which can be assessed via the quality factor of planar superconducting resonators. At Glasgow we have developed a new protocol that reduces fitting errors and minimizes measurement background effects in such measurements [6].

Electromagnetic filtering is essential for the coherent control, operation, and readout of superconducting quantum circuits at milliKelvin temperatures. Noise photons of higher frequencies, beyond the pair-breaking energies of the superconductor, cause decoherence and require spectral engineering before reaching the packaged quantum chip. In work at Glasgow, we carried out quantitative studies of this effect and developed dedicated compact cryogenic filters [7].

Quantum annealing using superconducting qubits

Work on quantum annealing using superconducting qubits has been led by our UCL group. The overall goal of this work was to develop novel types of interactions (e.g. XX and YY) between flux qubits to enable on-chip implementation of Hamiltonians which cannot be efficiently solved classically. Our numerical work [8] identified a scalable approach to speed-up in the maximum-independent-set problem utilising a single XX interaction. Ongoing experimental work focuses on the design of novel capacitive YY couplers for flux qubits.

One of the earliest application areas for quantum computing is in simulation of physics, simple examples of which can be shown in small-scale circuits. In a collaboration with Karlsruhe Institute of Technology, an analogue quantum simulation of the multistate Landau-Zener model was demonstrated, emulating the model's Hamiltonian using a superconducting qubit coupled to a bosonic mode ensemble. Different initial states were explored, revealing that the dynamic nature varies with the photon number in the resonator, and a greater coupling strength leads to a quasi-adiabatic transition, suppressing coherent oscillations [9].

Future directions

Following on from this QCS Hub research, it will now be important to combine scalable circuit engineering [1-3] with fast two-qubit logic and robust control techniques [4] to demonstrate high fidelity operation of medium-scale superconducting circuits with 10s of qubits. Combining such circuits with high quality signal conditioning [7], next-generation cryogenic systems with capacity for large devices, high signal density, and fast feedback control electronics will then enable an era of research focusing on error correction to begin, setting us on a path towards universal fault-tolerant quantum computing.

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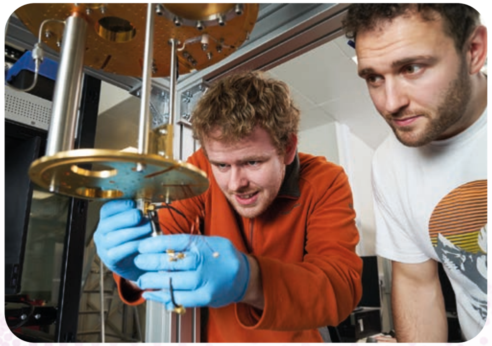


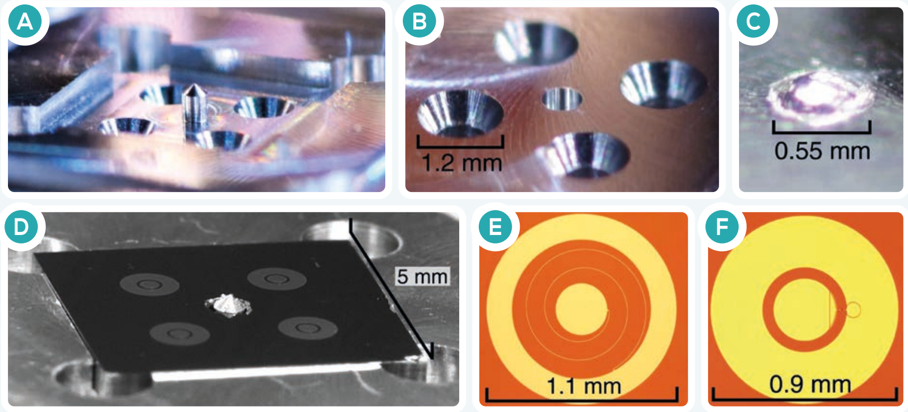
Featured Paper

High coherence and low crosstalk in a tileable 3D integrated superconducting circuit architecture

Peter A Spring, Shuxiang Cao, Takahiro Tsunoda, Giulio Campanaro, Simone Fasciati, James Wills, Mustafa Bakr, Vivek Chidambaram, Boris Shteynas, Lewis Carpenter, Paul Gow, James Gates, Brian Vlastakis, Peter J Leek, Science Advances **8**, eabl6698 (2022)

Building useful quantum computers requires us to build large scale circuits with many qubits, while also maintaining exceptionally high quantum coherence and fidelity of control. This paper shows that we can produce state-of-the-art quantum coherence and single-qubit gate fidelities in a four-qubit prototype of a fully 'tileable' circuit design.

Our circuit incorporates microwave engineering features that will enable it to reach arbitrarily large 2D lattices of qubits, as well as 3D integrated control wiring that means qubits will remain addressable as the architecture scales. The metrics of quantum coherence that we measure include the energy relaxation times of the qubits, T_1 ~ 150 μs and single-qubit gate of 0.02%, well below the threshold required for error correction in a fault-tolerant machine. The functionality required for two-qubit gates can now be easily integrated onto the circuits due to the simple circuit design that moves all control wiring off chip.



Optical images of cavity enclosure and circuit.
Ⓐ Enclosure base with cavity, central pillar, and four tapered through-holes for out-of-plane wiring access. Ⓑ Enclosure lid with a central cylindrical recess and identical through-holes for out-of-plane wiring. Ⓒ Cylindrical recess in the lid filled with a ball of indium. Ⓓ (Grayscale) Four-qubit circuit mounted inside the enclosure base. The four qubits are visible, arranged in a square lattice with 2-mm spacing. Ⓔ A spiral resonator and Ⓕ a transmon qubit with identical electrode dimensions to those in the device.

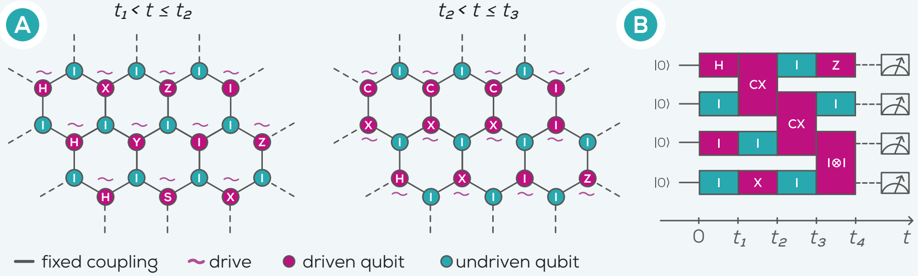
Featured Paper

Scalable and robust quantum computing on qubit arrays with fixed coupling

Nguyen H. Le, Max Cykiert, Eran Ginossar, npj Quantum Information 9, 1 (2023)

Large-scale quantum processors necessitate a large number of control signals for qubits and couplers, resulting in prolonged tuning up sessions where the processor is essentially offline. Here, we introduce a novel qubit layout and control scheme for reducing the number of control signals by half while enhancing gate resilience to environmental fluctuations and parameter drifts.

Our approach is based on driving a subarray of qubits such that the total multi-qubit Hamiltonian can be decomposed into a sum of commuting few-qubit blocks, and efficient optimisation of the unitary evolution within each block. We show that it is possible to realise a universal set of quantum gates with high fidelity on the basis blocks, and by shifting the driving pattern one can realise an arbitrary quantum circuit on the array. Allowing for imperfect Hamiltonian characterisation, we use robust optimal control to obtain fidelities around 99.99% despite 1% uncertainty in the qubit-qubit and drive-qubit couplings, and a detuning uncertainty at 0.1% of the qubit-qubit coupling strength. This robust feature is crucial for scaling up as parameter uncertainty is significant in large devices.



Ⓐ An example of implementing quantum gates on an array of qubits with fixed couplings. In any given step only a subarray can be driven. This subarray can be chosen to satisfy specific requirements so that the array's Hamiltonian can be decomposed into commuting few-qubit blocks. Each drive can implement a gate on the driven qubit, and through its combination with the fixed qubit-qubit couplings also implements an identity operator on the neighbouring undriven qubits. In the next step, a different subarray is driven for implementing gates on a different set of qubits. Here C-X on two adjacent qubits denotes the CNOT gate and the identity gate. Ⓑ Illustration of a quantum circuit in our scheme. The key feature is that any idle interval between gates is filled with an identity gate for preventing unwanted evolution due to the fixed couplings.

Diamond

Research Lead

Professor Jason Smith
University of Oxford

Jason Smith is Professor of Photonic Materials and Devices in the Department of Materials at the University of Oxford, and leads the Photonic Nanomaterials Group (PNG). His research focuses on the engineering of materials and devices at nanometre and micrometre length scales to control the interaction between light and matter as a route to new technologies. He is known primarily for his work on open optical microcavities and on the laser writing of colour centres in diamond. Jason is the founding Editor-in-Chief of the journal Materials for Quantum Technology (IOPP).

Introduction

Diamond as a material has the potential to hold a million qubits on a single centimetre-square chip which can be operated at convenient temperatures (4K or higher). Nuclear spins are used as quantum memories with long coherence times, while electron spins facilitate entanglement both by hyperfine coupling with the nuclei and by coupling to each other via an optical network.

Focus

The Hub's work in this area has focused on engineering these devices for quantum applications, using negatively charged nitrogen-vacancy (NV-) defects as the hosts for the electron spins.

One arm of our research has been materials engineering – the production of single NV- defects in diamond at specific locations so that they can be integrated with electronic and photonic subsystems. Our principal tool is laser processing with femtosecond pulses, which deliver sufficiently large amounts of energy to the diamond lattice – in very short bursts – to dislodge the carbon atoms. Our team pioneered this technique in 2016 and it has since been adopted by several other research groups worldwide.

There are two steps to the laser-writing of NV defects. Firstly a single, high-energy laser pulse is used to knock a few carbon atoms out of their lattice sites and create vacancies (the removed carbon atoms remain close by as so-called 'interstitials'). Secondly, a long sequence of lower energy pulses is applied which allows the vacancies to diffuse around randomly in the diamond lattice. All diamond has a small amount of nitrogen in it, and when a diffusing vacancy meets a nitrogen impurity atom it binds to it to form an NV defect. The extra electron to make NV- is readily captured since each nitrogen in the lattice donates an additional electron.

NV defects show strong characteristic fluorescence which allows detection of the individual defects as they are formed and which contains information about the defect properties. For the purposes of laser-writing, this provides valuable feedback on the fabrication process which allows a high degree of control.

One of the challenges in developing the laser writing process is that the basic science is not well understood. In parallel to the technology-focused work in the Hub we developed theoretical models to describe the physical mechanisms by which the diamond crystal is modified by the pulsed laser: a two-stage process in which the laser excites electrons in the diamond, and the electrons then relax delivering energy to the lattice. Understanding the details of the energy delivery mechanisms will be critical to exploiting the full potential of laser processing for defect engineering. A related question is how different defects in the diamond interact with each other. Rather like chemistry performed inside a crystal, the nitrogen impurity atoms, vacancies and interstitial defects all mix together, experiencing attractive and repulsive forces, and undergo reactions which involve the sharing and exchange of electrons and the formation of new complexes.

Within the first three years of the Hub, the focus of the diamond effort was the high yield fabrication of coherent NV centres into diamond membranes as the basis for fabricating chips with arrays of spin qubit clusters coupled to an optical network. The key advance made during this period was the deterministic writing of single NV centres into high purity diamond with nitrogen at parts-per-billion levels.

This result came with significant improvements to the coherence properties of the NV centres produced. Spin coherence (T2) times exceeding 100μs were measured, and optical transition linewidths below 100MHz with a yield of around 20%. The spin coherence is still somewhat short of our target of T2 › 500μs, but further improvements to the process are likely to meet this goal. We have also developed a process route for fabricating uniform diamond membranes of 5μm thickness and are in the process of bringing these elements together.

To complement the work on laser writing we investigated the fluorescence blinking observed previously during laser annealing by theoretical modelling of diamond defect interactions using density functional theory [1]. Our tentative conclusion from this work is that the blinking results from the intermittent quenching of NV fluorescence by a nearby carbon self-interstitial as it diffuses through the diamond lattice during the annealing process.

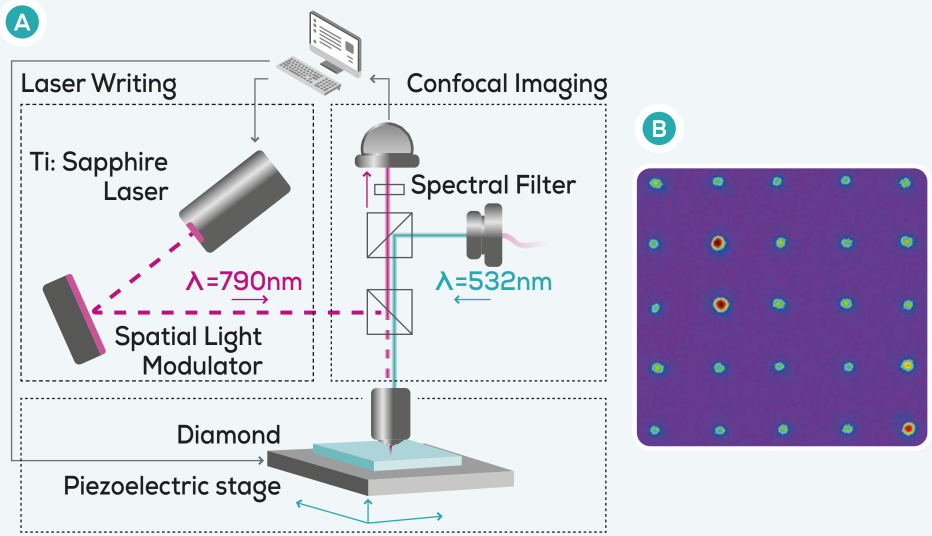
In years 4 and 5 of the QCS Hub our diamond research shifted emphasis, and joined up with our photonics team (see Photonics, page 27) to explore the hybridisation of diamond NV defects with photonic chips

Featured Paper

Laser writing of individual nitrogen-vacancy defects in diamond with near-unity yield

Yu-Chen Chen, Benjamin Griffiths, Laiyi Weng, Shannon S. Nicley, Shazeaa N. Ishmael, Yashna Lekhai, Sam Johnson, Colin J. Stephen, Ben L. Green, Gavin W. Morley, Mark E. Newton, Martin J. Booth, Patrick S. Salter, and Jason M. Smith, Optica 6, 662 (2019).

The formation of a nitrogen-vacancy defect in diamond occurs when a vacancy diffusing in the diamond lattice meets and binds to a nitrogen impurity atom. Since the diffusion process and the initial positions of the nitrogen and vacancy are all random, it is not possible to predict exactly when an NV defect will be formed, or indeed how many will be formed if many nitrogen atoms and vacancies are present. In this paper we show that single NV defects can be created deterministically by monitoring for their characteristic fluorescence while the diffusion is taking place. The apparatus is entirely optical with an ultrafast laser used to create and diffuse the vacancies and a common microscope objective used for writing and fluorescence monitoring. The monitor allows us to observe not only the number but also the orientation of the NV defects in the diamond lattice, offering potential for advanced engineering of defect arrays.



Deterministic laser writing of NV colour centers in diamond. Ⓐ Schematic of the laser writing apparatus. Ⓑ Fluorescence image of a high-yield 5 x 5 array of single NV centers on a 2 um square grid.

Photonics

Research Lead

Professor Anthony Laing
University of Bristol

Anthony Laing is a Professor of Physics at the University of Bristol and Co-Director of its Quantum Engineering Technology Labs. He leads the photonics work-package for the QCS Hub, and he is co-founder and CEO of Duality Quantum Photonics. His interests span from foundations of physics to the research, development, and commercialisation of photonic quantum technologies. He has developed programmable photonic circuits and their applications to quantum computing, simulation and other quantum technologies. He invented the reference-frame-independent quantum key distribution protocol.

Introduction

The Hub's Photonics work package focused on developing techniques and applications of quantum information processing at the single or few photon level.

Teams led by Anthony Bennett at Cardiff University, and Peter Mosley at Bath University worked on the interface of single photon sources with quantum memories. They targeted developing frequency conversion with photonic crystal fibres to allow compatibility between quantum dot sources and vapour-based atomic quantum memories.

Meanwhile, Anthony Laing at Bristol University, and Ian Walmsley, Steve Kolthammer, and Raj Patel at Imperial College London, have developed quantum simulators based on integrated photonics. This enabled the simulation of computationally intensive tasks known to be intractable to conventional computers, with applications to molecular dynamics and graph theory.

In 2022, the Photonic effort was joined by the Diamond team, led by the group of Jason Smith at Oxford University, to couple NV centres in diamond membrane micro-cavities with photonic circuits to enable deterministic non-linear interaction; a crucial building block towards the realisation of entangling gates and scalable quantum computing.

Single photon sources and atom-vapour-based memories

In the course of the QCS Hub, single semiconductor quantum dots have been shown to be amongst the most promising quantum light sources, offering device-to-detector efficiencies over 50% and near unity indistinguishability, whilst maintaining their natural single-photon character and intrinsic GHz photon emission rate.

This means they offer the potential for scalable linear optical quantum computing, and impressive experiments by Basel and USTC have been published in the last few years. At the same time, the quantum dots' emission wavelength is typically not compatible with telecom fibres or atomic memories, meaning that additional efforts are required to couple them efficiently.

Cardiff has developed a single-photon source based on a single quantum dot in a monolithic semiconductor cavity. Working with the National Epitaxy Facility in Sheffield, they optimised the material growth and manufactured devices in the Cardiff cleanroom with state-of-the-art quality factor, emission coupling factor and the ability to be mass-produced at scale. Using resonant excitation in a dark field microscope, they have shown that even modest quality factor cavities can have multiphoton emission fractions of a few percent, indistinguishability over 95% and deliver a high photon rate. The quality of the cavities has allowed Cardiff to study the often-overlooked effect of non-cavity modes which are spectrally broadband, and so hard to directly probe, but play a key role in device performance.

The work at Bath has focused on interfacing these quantum dot sources with fibre networks to optimise the collection of light, and successful coupling was achieved using both microstructured fibre and tapered conventional fibre.

Bath also progressed towards the realisation of a hollow fibre vapour cell quantum memory after measuring an optically-induced phase shift of a signal beam close to the Rb two-photon absorption resonance around 778nm, which is reported in a manuscript submitted for publication [1]. Bath researchers also demonstrated fast, low-loss optically-driven port switching in a Rb-filled ring cavity, exceeding the goals of the associated target milestone. The team is building an additional cavity locking system which will enable them to achieve publication-quality results before the end of the Hub.

In order to convert dot emission to telecom wavelengths they have been working on frequency conversion. Here they demonstrated Bragg-scattering four-wave mixing frequency conversion in photonic crystal fibre between 925nm, within the range of InGaAs quantum dot emission, and 1550nm. This creates a bi-directional interface suitable to convert the Cardiff quantum dots' light around 930nm to telecom band at 1550nm for further processing, and draws on their recent experience of developing ultra-tuneable quantum frequency conversion interfaces [2]. Figure 1 shows (A) a cross-section of the fibre used, and (B) a spectrum from a conversion experiment.

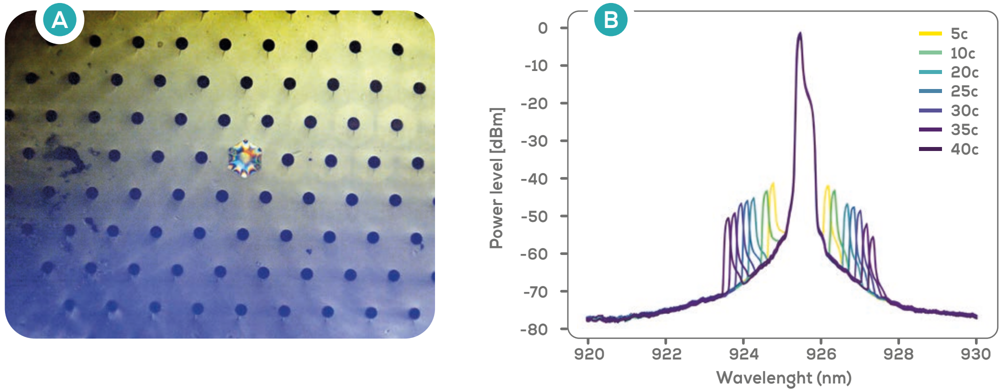


Figure 1: Ⓐ New fibre design fabricated for the conversion of single photons to and from the C-band.

Ⓑ Spectrum of FWM sidebands around a 925nm pump; these sidebands are converted from 1550nm. Sidebands tune with input wavelength near 1550nm which is controlled via laser diode temperature as labelled in the legend.

Complexity of quantum computing and photonic quantum simulators

Simulating the dynamics of complex quantum systems is a promising application of quantum computers. While it is known that this task is intractable for conventional computers, it is achievable with quantum hardware by mapping the system of interest to another quantum system simpler to control and measure.

Gaussian Boson Sampling (GBS) is a technique involving the interference of squeezed states of light, and photon detection. The structure of the interferometer and the type of input light affect the output statistics, which can be related to vibronic transitions of molecules, therefore effectively simulating the behaviour of such a system. Additional applications have been explored, such as graph theory to dense subgraph and max clique finding.

Imperial College London has been studying the hardness of the GBS task, and extensions of GBS to include additional operations acting on Gaussian states to uncover new applications and regimes where quantum advantage may be found. This work led to several key milestones. In collaboration with Bristol, Imperial developed a new classical algorithm for benchmarking GBS devices which has been adopted in the community for benchmarking real devices exhibiting quantum advantage [3].

Imperial reported the first time-bin GBS experiment and were the first to apply it to solve graph problems [4]. Imperial were also the first to study the role of displacements in a GBS experiment and built on this to develop semiclassical models and complexity-theoretic proofs to study the regimes of quantum advantage when displacements are applied [5]. Collectively, this work motivated the study of applications of GBS, including drug discovery and the simulation of vibronic spectra of real molecules [6]. Other technical innovations include developing integrated circuitry with more compact unitary decompositions and boosting the speed at which transition edge sensors operate.

To mitigate the effects of unavoidable errors in the simulations, the Bristol team implemented error correction techniques in logical qubits [7] using entangled graph states, and a novel approach based on high timing resolution at a hardware level [8]. Both techniques can help progress towards the realisation of algorithms in the quantum supremacy regime.

Deterministic non-linear interactions in diamond membrane structures

Diamond is a material with a strong potential to hold many qubits that can be well isolated and addressed. The nuclear spins of the carbon atoms surrounding a defect in the lattice are used to store the quantum information with long coherence times, while the electron spins of the defects themselves are used to entangle them together via the use of optical photons.

Mastering the fabrication process of high-quality defects is critical to allow reproducibility and scalability. Here, NV- centres are created with a near-unit yield using a laser writing method developed and pioneered by the Oxford team [9]. First, high-energy laser pulses are applied to dislodge carbon atoms and create vacancies, and then, sequences of lower-energy laser pulses are used to diffuse the vacancies randomly around the lattice until they meet nitrogen atoms to form NV defects.

Another important aspect to obtain bright centres is to integrate them into optical micro-cavities to enhance the interaction of the defect with external light (Figure 2). The Oxford team explored two approaches to make suitable micro-cavities for NV centres. The first one involves ion beam milling of a 30μm single crystal CVD-grown diamond membrane. Using this technique, the cavity features are demonstrably smooth and repeatable (Figure 2b,c) and reveal clear mode structure (Figure 2d). The second method relies on the exposition of a spherical pattern into positive photoresist and subsequently heating the sample up. This creates lens-type structures due to the non-cross-linking of positive photoresist. After ICP/RIE etching, cavity features can be repeatably and deterministically produced (Figure 3).

The monolithic micro-cavities need to be able to be 'tuned' on to resonance with the zero-phonon line of the embedded NV centre, and the best means to achieve this is to introduce a secondary non-linear material to the cavity, whose refractive index changes in response to an applied electric field. This changes the optical path length of the cavity and consequently can provide in-situ cavity tuning.

Strontium Barium Niobate (SBN) is an excellent candidate material for this purpose, and substantial progress has been made to grow this material by pulsed laser deposition (PLD), to characterise the microstructure, and to understand the best means to integrate the material with the diamond membrane.

The SBN thin-film material has been grown by PLD at Oxford. To gain the desired strong tuning benefits of this material, it needs to be encouraged to grow slightly off of its preferred orientation axis. This has been achieved with optimised growth conditions and substrates. The desired optical birefringence has been observed in the as-grown thin film. Work is ongoing to better understand the microstructure and optical properties, and to realise the complete, tuneable microcavity devices.

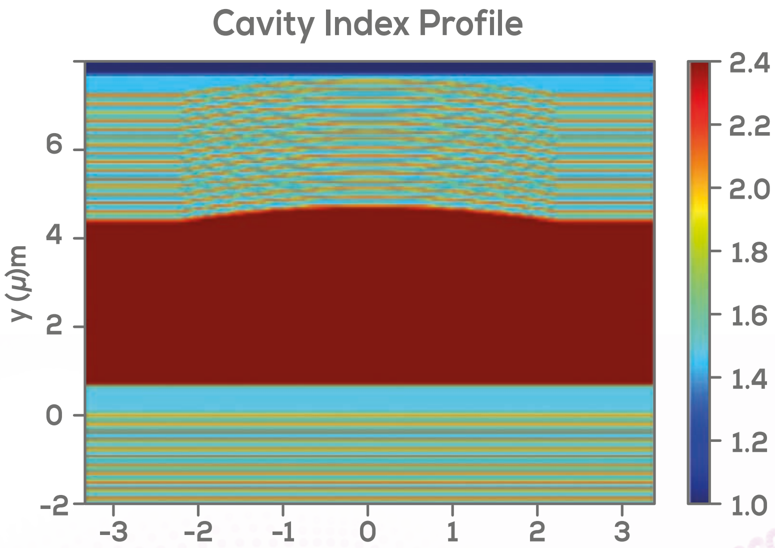
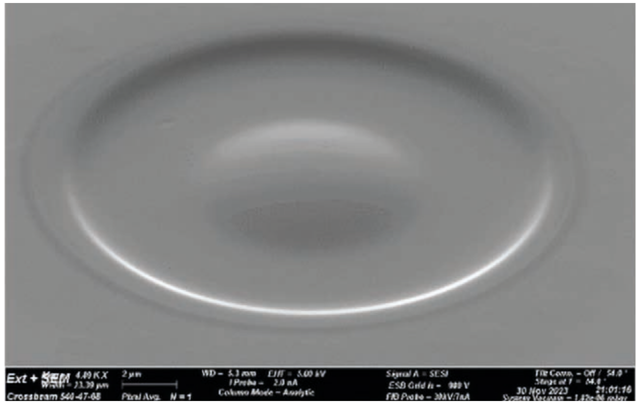
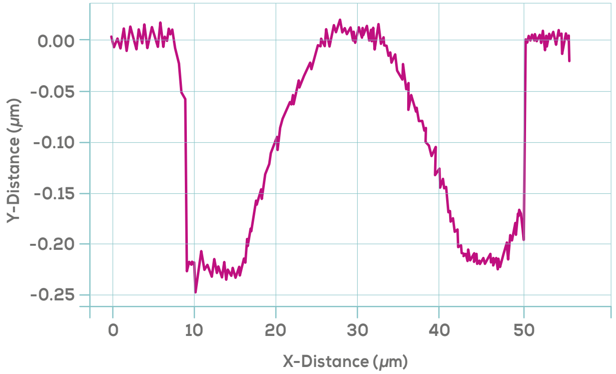


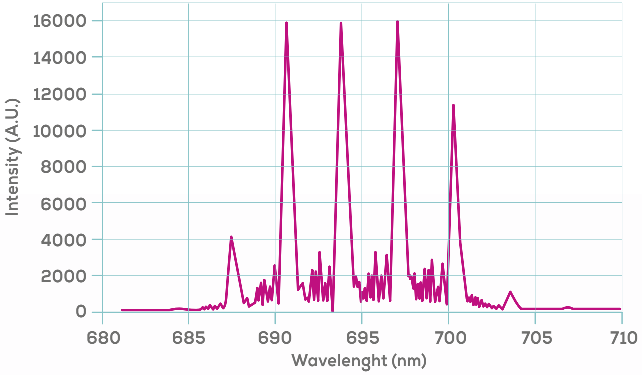
Figure 2: Ⓐ Cross-section schematic of hybrid diamond-EO material microcavity.



Ⓑ SEM image of a 'microlens' cavity mirror feature produced using FIB milling.



Ⓒ Measured surface profile of one such feature.



Ⓓ Optical transmission spectrum of a cavity formed using metallic mirrors showing the mode structure.

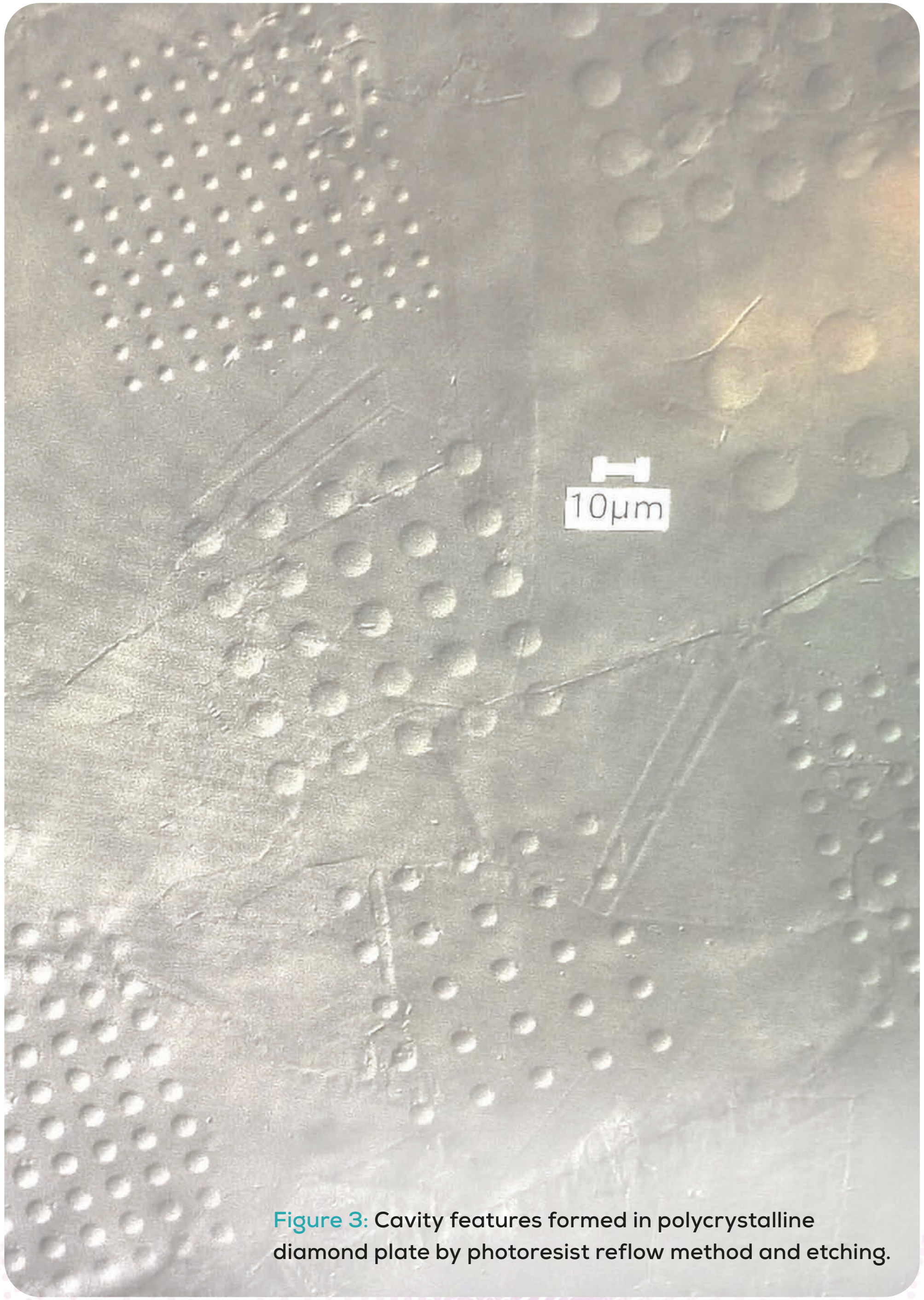


Figure 3: **Cavity features formed in polycrystalline diamond plate by photoresist reflow method and etching.**

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[3] The boundary for quantum advantage in Gaussian boson sampling, Bulmer et al., Sci. Adv.8, eabl9236 (2022)

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[7] Error-protected qubits in a silicon photonic chip, Vigliar et al., Nat. Phys. 17, 1137–1143 (2021)

[8] On-chip quantum information processing with distinguishable photons, Yard et al., preprint arxiv:2210.08044 (PRL In press)

[9] Laser writing of individual nitrogen-vacancy defects in diamond with near-unity yield, Chen et al., Optica 6, 662-667 (2019)

Featured Paper

On-chip quantum information processing with distinguishable photons

Patrick Yard, Alex E. Jones, Stefano Paesani, Alexandre Maïnos, Jacob F. F. Bulmer, Anthony Laing, preprint arxiv:2210.08044 (Accepted in PRL)

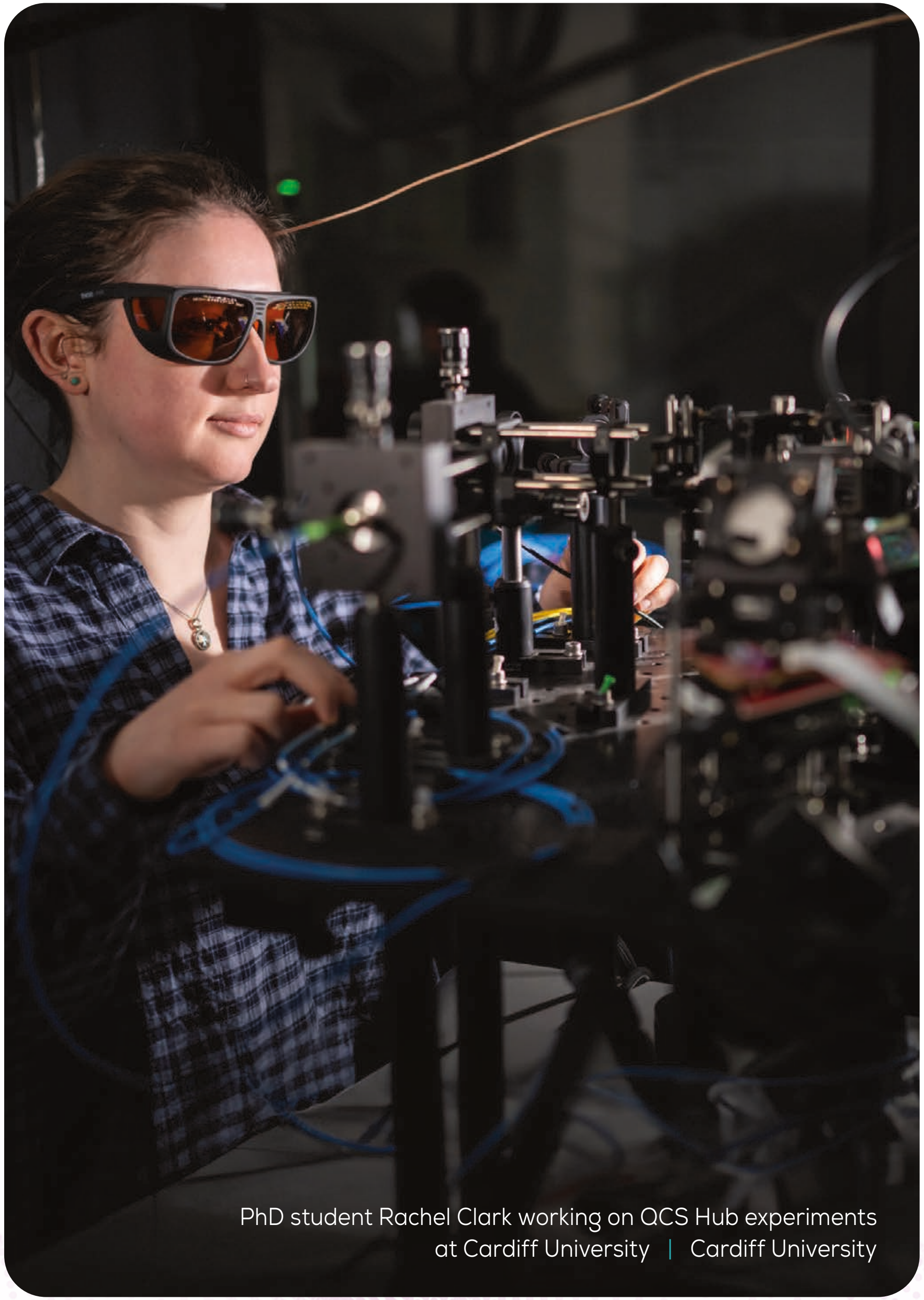
Photonic quantum technologies fundamentally rely on photon interference. Especially, it requires a high degree of indistinguishability between photons coming from various sources. However, it is challenging to fabricate many identical sources, and any fabrication flaws will in turn degrade the interference visibility. Here, it is demonstrated that hardware-based error mitigation is possible by leveraging a high timing resolution. Indeed, the photon frequency distinguishability is erased through the time-energy uncertainty relation. By increasing the timing resolution from 200ps to 20ps, the interference visibility between independent photons generated from micro-ring resonators was improved by 20%. This can in turn increase the fidelity of entangling operations, potentially bringing them closer or below the fault-tolerance threshold required for scalable quantum computing. Additionally, the improved visibility is offering a better complexity in boson sampling experiments, giving them an even more striking quantum advantage.

Featured Paper

Ultratunable Quantum Frequency Conversion in Photonic Crystal Fibre

K. A. G. Bonsma-Fisher, P. J. Bustard, C. Parry, T. A. Wright, D. G. England, B. J. Sussman, and P. J. Mosley, PRL 129, 203603 (2022)

Photonic Crystal Fibres (PCF) are structures with a high degree of customisation, enabling them to attain specific propagation properties, in particular group velocity dispersion. They are typically made by assembling a macro-scale preform which is then heated up and pulled to obtain a micro-scale fibre with a preserved structure. Here, it is demonstrated that such a fibre can allow a nonlinear process called four-wave mixing to happen efficiently over a wide range of wavelengths. This permits the tuneable conversion of signal photons from a fixed wavelength 1551nm to target photons in the range 1226-1482nm or vice-versa. This broad range is achievable with a single fibre and a tuneable pump, which would allow the interfacing of various components working with different wavelengths inside a quantum network, such as atomic memories, or quantum dot sources or help sensing at wavelengths where detectors are usually inefficient.


PhD student Rachel Clark working on QCS Hub experiments at Cardiff University | Cardiff University

Silicon Quantum Processors

Research Lead

Professor John Morton

UCL

John Morton is Professor of Nanoelectronics & Nanophotonics at the London Centre for Nanotechnology at UCL, and Director of UCL Quantum Science and Technology Institute, UCLQ. His group studies the quantum dynamics of electron and nuclear spins in materials and nano-devices, towards applications in quantum computing and sensing.

His awards include the Raymond and Beverly Sackler International Prize in Physical Sciences, Moseley Medal and Prize (Institute of Physics), Nicholas Kurti European Science Prize, and Cavendish Medal (SET for Britain). He is a recipient of European Research Council Starter and Consolidator Grants and is a Fellow of the Institute of Physics. John has co-founded three companies in the field of quantum technology, covering quantum computing hardware and software.

Introduction

Silicon chips form the basis of most conventional computing. Semiconductor firms have been optimising their processes for decades and are able to fit billions of transistors on to a single chip. QCS Hub researchers are exploring how the same technology can also be used for quantum computing. This work aims to harness the decades and trillions of dollars of investment in perfecting fabrication techniques in CMOS to build dense, high-fidelity qubits and multi-qubit gates. CMOS is a proven platform able to produce billions of devices per chip with high yield and reproducibility and allowing integration between quantum devices and classical control on the same chip. Silicon spin qubits have long coherence times, and have demonstrated fault-tolerant fidelities exceeding 99.5%, and fast gate speeds, of the order of 100ns. In principle, a qubit density of $10^7 - 10^8$ qubits per cm^2 could be achieved.

Our work in this area has focused on two main goals: developing qubits made in CMOS foundries and on-chip qubit transfer (qubit shuttling). The team is based at UCL, working with QCS Hub partner Quantum Motion, a quantum computing scale-up.

Since the launch of the QCS Hub the team has made a series of advances. In March 2021, we performed the first measurement of a single electron spin in a CMOS device that has been fabricated using industrial-grade manufacturing at the 300mm wafer scale. This was an important milestone showing that fabrication techniques similar to those used in conventional CMOS transistors can be used to achieve structures for the trapping and readout of single electrons. In that work we demonstrated a 99% measurement fidelity within 20 microseconds for single-shot read-out of an electron spin. Moreover, the corresponding spin lifetime (T_1), of up to 9 seconds, is amongst the longest measured for an electron spin in a solid-state device. The result was published in April 2021 and received widespread press in national outlets such as the BBC World Service (radio), Telegraph (newspaper) and New Statesman (magazine) [1].

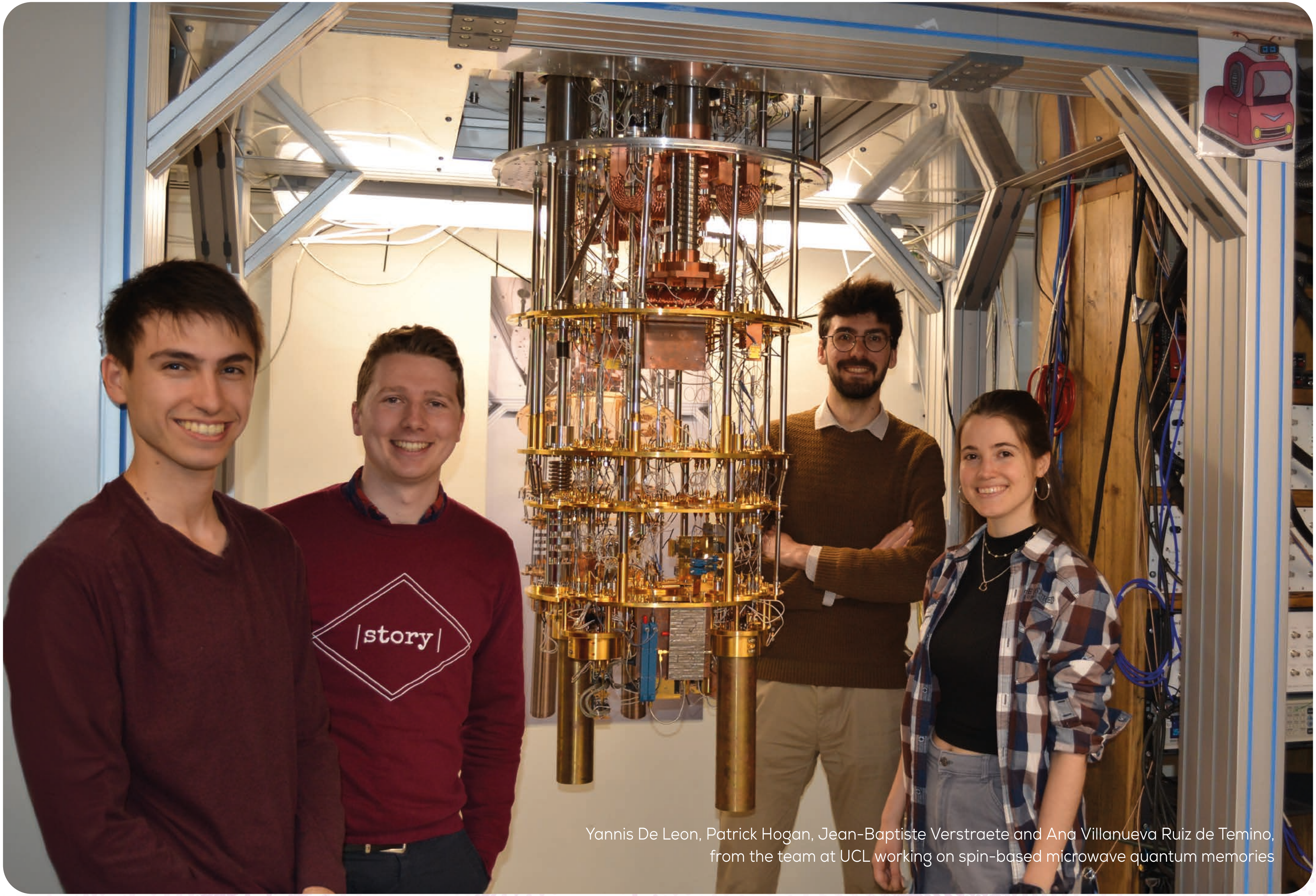
After this initial result demonstrating the promise of fabrication techniques similar to those used in conventional CMOS transistors, the team has focused on improving all the constituent elements required such as readout, control, architecture, and mass characterization to produce a viable unit cell that can be easily scaled.

Readout advances

Fast spin readout has been shown using single-electron transistors (SETs). However, a SET requires at least three electrodes and two charge reservoirs, significantly limiting possible architecture designs.

Dispersive sensing offers the potential of scalable unit cells by avoiding the need for multiple charge reservoirs. In 2023, we presented two complementary demonstrations of fast high-fidelity single-shot readout of spins in silicon quantum dots using a radio-frequency single-electron box. The sensor, despite requiring fewer electrodes than conventional detectors, performs at the state of the art, achieving spin readout fidelity of 99.2% in less than 6μs. Our results put dispersive charge sensing at the forefront of readout methodologies for scalable semiconductor spin-based quantum processors [2].

So far, demonstrations of planar MOS quantum dots have been restricted to architectures where sensors are co-linear with the qubit array, limiting scalability. Achieving readout fidelity at the level of control operations has also remained challenging. However, at the 2024 APS March Meeting, work package PhD student Constance Lainé presented work that addresses both limitations.



Yannis De Leon, Patrick Hogan, Jean-Baptiste Verstraete and Ana Villanueva Ruiz de Temino, from the team at UCL working on spin-based microwave quantum memories

In this work the team demonstrated single-shot spin readout with fidelity above 99.9% measured in 200μs in a planar MOS quantum dot array fabricated using a 300mm wafer process. The team used a single electron box (SEB) to measure the two-electron spin state of a double quantum dot using Pauli spin blockade. The sensor and qubit dots are placed in parallel channels of a bilinear array of quantum dots, forming a compact unit cell. The high fidelity is achieved thanks to the tunability of the structure that allows (i) optimization of the tunnel rate of the SEB for enhanced signal and (ii) tuning of the coupling between the double quantum dots using a J-gate, leading to an enhancement of the singlet-triplet relaxation time from 4μs to 0.5s. Overall, this work demonstrated sensing in a compact unit cell with state-of-the-art fidelity, providing a path to scalable high-connectivity bilinear qubit arrays [3].

Developing new architectures

Alongside improvements in readout and control, the team has explored new architecture designs (see featured paper, *Quantum Pipeline*). To help increase the pace of discovery the team is developing tools and methods that enable the mass characterizations of many devices (see featured paper *Rapid cryogenic characterisation of 1024 integrated silicon quantum dots*).

In 2023, the team characterised one of our new designs: a maximally entangling gate on a two-electron spin state defined in a double quantum dot. The dots were hosted in a planar MOS structure in natural silicon, fabricated using a hybrid 300mm optical and electron beam lithography process. This was paired with fast readout via radio-frequency dispersive measurement, enabled by an off-chip 512MHz superconducting resonator, allowing projective measurement of the two-electron spin states. We demonstrated coherent control via the exchange interaction to perform a $\sqrt{\text{SWAP}}$ gate in $\leq$ 8ns within a decay time of $T_2^{\text{SWAP}} \approx$ 400ns, leading to a gate quality factor $\approx$ 25 at this control point. The combination of this maximally entangling gate with dispersive readout in a device manufactured using 300mm wafer scale processing presents a simultaneous demonstration of many of the key ingredients required for a scalable unit cell for a silicon-based quantum processor [4].

Quantum memories

In the final two years of the QCS Hub, the work package team began a new activity to explore using the second-long coherence times of donor spins in silicon as microwave quantum memories.

As in conventional computing, memories for quantum information benefit from high storage density and, crucially, random access, or the ability to read from or write to an arbitrarily chosen register. However, achieving such random access with quantum memories in a dense, hardware-efficient manner remains a challenge. We introduced a protocol using chirped pulses to encode qubits within an ensemble of quantum two-level systems, offering both random access and naturally supporting dynamical decoupling to enhance the memory lifetime. We demonstrated the protocol in the microwave regime using donor spins in silicon coupled to a superconducting cavity, storing up to four weak, coherent microwave pulses in distinct memory modes and retrieving them on demand up to 2ms later. This approach offers the potential for microwave random access quantum memories with lifetimes exceeding seconds, while the chirped pulse phase encoding could also be applied in the optical regime to enhance quantum repeaters and networks [5].

[1] Spin Readout of a CMOS Quantum Dot by Gate Reflectometry and Spin-Dependent Tunneling. Ciriano et al., PRX Quantum 2, 010353 (2021)

[2] Fast High-Fidelity Single-Shot Readout of Spins in Silicon Using a Single-Electron Box. Oakes et al., Physical Review X, 13, 011023 (2023)

[3] High-fidelity dispersive spin readout in a scalable unit cell of silicon quantum dots. Lainé et al., APS March Meeting Abstracts, S46.00009 (2024)

[4] Dispersively sensed entangling gate in silicon quantum dots fabricated on 300mm wafers. Chittock-Wood et al., APS March Meeting Abstracts. Z74.00009 (2023)

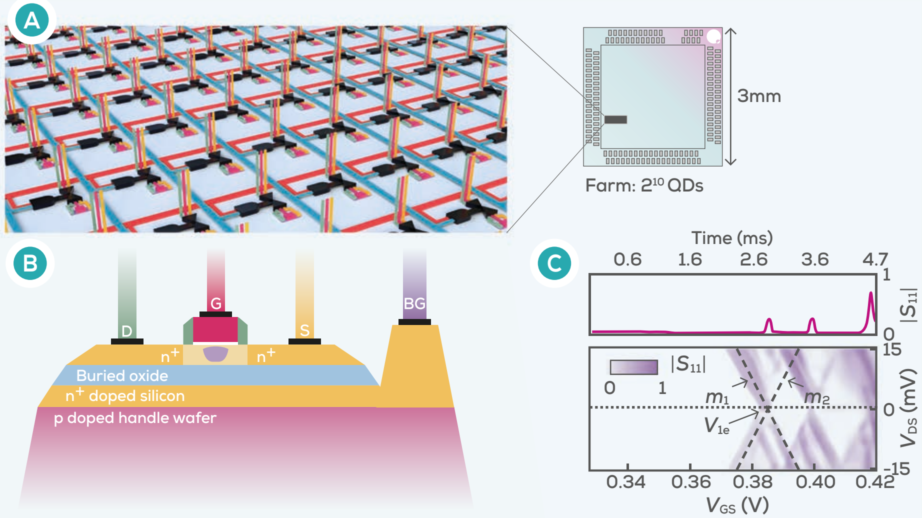
[5] Random-Access Quantum Memory Using Chirped Pulse Phase Encoding. O'Sullivan et al., Physical Review X 12, 041014 (2022)

Featured Paper

Rapid cryogenic characterisation of 1024 integrated silicon quantum dots

Edward J. Thomas, Virginia N. Ciriano-Tejel, David F. Wise, Domenic Prete, Mathieu de Kruijf, David J. Ibberson, Grayson M. Noah, Alberto Gomez-Saiz, M. Fernando Gonzalez-Zalba, Mark A. I. Johnson, John J. L. Morton, arXiv:2310.20434 (2023)

We demonstrate the integration of 1024 silicon quantum dots with on-chip digital and analogue electronics, all operating below 1K. A high-frequency analogue multiplexer provides fast access to all devices with minimal electrical connections, enabling characteristic data across the quantum dot array to be acquired in just 5 minutes. We achieve this by leveraging radio-frequency reflectometry with state-of-the-art signal integrity, reaching a minimum integration time of 160ps. Key quantum dot parameters are extracted by fast automated machine learning routines to assess quantum dot yield and understand the impact of device design. Our results show how rapid large-scale studies of silicon quantum devices can be performed at lower temperatures and measurement rates orders of magnitude faster than current probing techniques, and form a platform for the future on-chip addressing of large scale qubit arrays.



Ⓐ 3D schematic render of the 1:1024 multiplexer, with analogue access (green, pink, yellow) to each quantum dot device controlled by row-column addressing (red and blue wires). This farm of devices occupies a small section of a 3 mm×3 mm silicon die. Ⓑ Schematic cross-section of a single transistor with a quantum dot (purple) below the gate and situated between the drain and source. The region where the quantum dot forms is undoped silicon. Ⓒ Example 2D map showing a normalised device response (colour scale) as a function of source-drain and gate voltages. The dashed line shows an automated fit to the first measured Coulomb blockade oscillation. The top panel shows a line cut at VDS = 0 V (indicated by the dotted line), with the time-axis aligning with the voltage axis in the bottom panel.

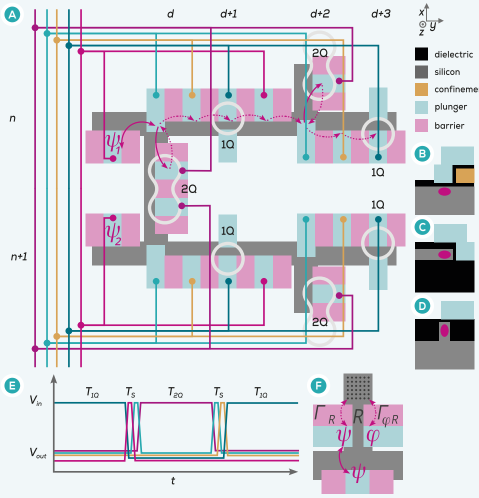
Featured Paper

Pipeline quantum processor architecture for silicon spin qubits

SM Patomäki, MF Gonzalez-Zalba, MA Fogarty, Z Cai, SC Benjamin, JJL Morton, npj Quantum Inf 10, 31 (2024)

We propose a NISQ processor architecture using a qubit 'pipeline' in which qubit states travel through a layered physical array of structures which realise single and two-qubit gates, instead of spatially static qubits to which quantum operations are performed. We call this approach the pipeline. In exchange for simplifying run-time control, a larger number of physical structures is required. To reduce the number of physical structures required, qubit states can be 'pipelined' densely through the arrays for repeated runs. Silicon spin-qubit platforms are especially well suited to this approach due to their high qubit density and scalability. We have designed the pipeline to operate using exclusively global control techniques which reduce the number of classical computing resources needed to operate the processor while also tolerating a high degree of qubit variability and noise.

In this implementation, we describe the physical realisation of single and two qubit gates which represent a universal gate set that can achieve fidelities of F ≥ 0.9999, even under typical qubit frequency variations.



Ⓐ Unit cell of a qubit pipeline, realised as a weaved grid of silicon channels (dark grey grid) which may be defined by etching or electrostatically by depletion gates (not shown). Overlapping metal gates (coloured rectangles) are used to confine, shuttle and manipulate electron spin qubits within the channels. Connectivity for five-stage shuttling is shown as coloured lines where all sites mod 5 (for example, those controlling two subsequent 2Q sites) are connected to the same ac voltage source. All barrier gates receive individual dc biases. Ⓑ - Ⓓ Side views of different gate stacks which could be used in this implementation, including Ⓑ planar MOS, Ⓒ SOI nanowire, and Ⓓ finFET. Quantum dots (magenta blobs) are confined using etched silicon or confinement gates (light yellow). Ⓔ Sketch of the shuttling pulse sequence (relative pulse durations not to scale). Voltages Vin(Vout) are those at which single (zero) electron occupancy of the QD becomes the ground state. Single- and two-qubit gates are separated by short shuttling steps–in general, the number of shuttling steps depends on the exact gate layout, and depend on e.g. footprints required for routing. Ⓕ Structures for local electron reservoirs (R), for spin readout (with an auxiliary state **φ**), and hence for preconfiguration of quantum states **ψ**. The operation of these structures, which can be placed along pipes between ***d+1** and **d+2*** (see Ⓐ), is discussed further in the paper.

Cold Atoms

Research Lead

Professor Andrew Daley
University of Oxford

Andrew Daley is a theoretical physicist who works closely with experimental teams on the development of next generations of quantum computing and quantum simulation platforms, especially with neutral atoms. He has been a Professor of Theoretical Quantum Optics at the University of Strathclyde in Glasgow for the past 10 years, and recently took up a position as Professor of Quantum Physics at Oxford University.

As well as leading the Hub's work on cold atoms he is Principal Investigator of the EPSRC Programme Grant on Quantum Advantage in Quantitative Quantum Simulation, and was previously in the leadership team of the EU Quantum Technologies Flagship project on Programmable Atomic Large-Scale Quantum Simulation.

Introduction

Over the duration of the QCS Hub, we have made substantial progress in the programmability and control of platforms for quantum simulation based on ultracold neutral atoms.

Cold atoms systems are based around two main approaches to quantum computing and simulation. The first is to load atoms into arrays of optical tweezers, where atoms are trapped in arrays of tightly focused laser traps, and these hold the atoms which can then be manipulated with microwaves and additional laser fields. The second approach is analogue quantum simulation with moving atoms where atoms move in potentials made of laser light.

Progress

During recent years, international groups working with optical tweezers have demonstrated the ability to trap and manipulate more than 1000 atoms in these arrays. There has also been substantial UK progress, with the group of Jonathan Pritchard at the University of Strathclyde demonstrating the highest fidelity single-qubit gates in an array of more than 100 qubits. In these systems, two-qubit gates between atoms in different tweezers are performed by using additional laser drives to excite them to high-lying electronic excited states (known as Rydberg excitations), which enable strong interactions between distant qubits.

Internationally, the state of the art is two-qubit gates with over 99.5% fidelity, and the large upside of these platforms for quantum computing is the ease with which we can produce and control large numbers of identical qubits. The biggest challenges for these platforms are in realising fast operations, especially for the readout of qubits as we develop towards error-corrected systems.

With the second approach, analogue quantum simulation with atoms moving in potentials made of laser light, a so-called optical lattice can be realised for example by loading cold atoms in standing waves of laser light, mimicking the crystals in which electrons move in solid-state systems. In these optical lattice platforms, we have separate (time-dependent) control of the crystal structure and the interactions between atoms. These allow us to implement and study models that are both fundamental and challenging in solid-state physics, allowing us to test the building blocks of our understanding of modern solid-state materials.

The effective computational problem of determining the dynamics of interacting microscopic particles in such a setting are widely understood to be exponentially complex to simulate on classical computers. By implementing them in the laboratory we can observe their properties and effectively solve the corresponding models. Both in the UK and internationally we now have systems ranging from a few tens of highly controlled atoms up to thousands of atoms moving in optical potentials. The challenges going forward are to develop the level of local control and readout necessary to manipulate and measure these systems on the level of single atoms and single lattice sites, to increase the precision of the calibration of all model parameters, and to understand how to make use of these to extract useful information beyond that which can be accessed through calculations on classical supercomputers.

Within the Hub, we have been addressing these challenges within our analogue simulation platforms at the University of Strathclyde (led by Stefan Kuhr) and the University of Cambridge (Ulrich Schneider). They have made substantial advances in the bespoke control of optical lattice potential for quantum simulators, including developing and testing individual control of cold atoms in optical lattices, manipulating the potential landscape in which they move by using spatial light modulators, and by combining optical lattices with optical tweezers which impose a potential on top of an existing optical lattice. This work is in collaboration with the theory team of Andrew Daley (University of Strathclyde, University of Oxford), who are investigating new calibration and control techniques for enhancing existing experimental systems and for developing potential use cases of these systems.

Through a Partnership Resource Fund (PRF) project, led by Jonathan Pritchard (University of Strathclyde), we are also connecting with the tweezer array platform noted above for quantum computing. As well as connecting to a potential digital platform, these offer the possibility for mapping optimisation problems on to neutral atoms in the near term. It was in these experiments that a record fidelity for single-qubit gates was realised, with average gate errors of $7(2) \times 10^{-5}$ on a 225 site atom array.

In experiments at the University of Strathclyde, we have optimised the generation of projected and holographic light potentials. Our modelling and experimental developments have allowed us to generate potentials with < 2% RMS error and up to 40% diffraction efficiency, and to accurately control the addition or removal of single sites in an optical lattice potential.

This ability to control the system with repulsive potentials is demonstrated in figure 1 within our bosonic quantum gas microscope setup, and has led to work simulating doped systems from solid state physics as well as disordered systems. This work has been supported by the theory team, who have both explored the connection of these systems to applications, performing classical numerical calculations to benchmark the experiments, and who have also worked on new techniques for adiabatic state preparation in experiments. See the featured papers on the following page for examples.

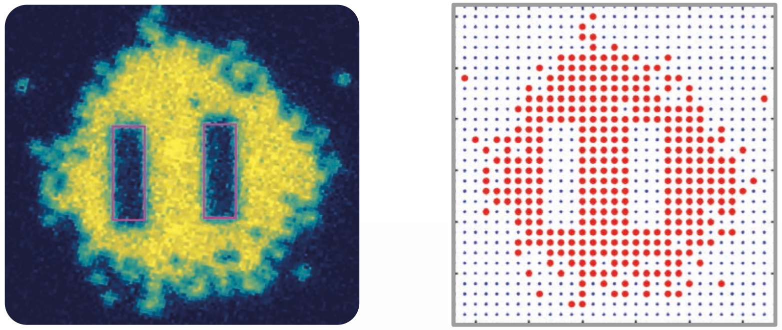


Figure 1. Techniques developed within the Hub allow experimentalists to control the energy of atoms in optical lattices at the level of single lattice sites, an important step towards more programmable quantum simulation of models relevant for describing solid-state materials (image: University of Strathclyde)

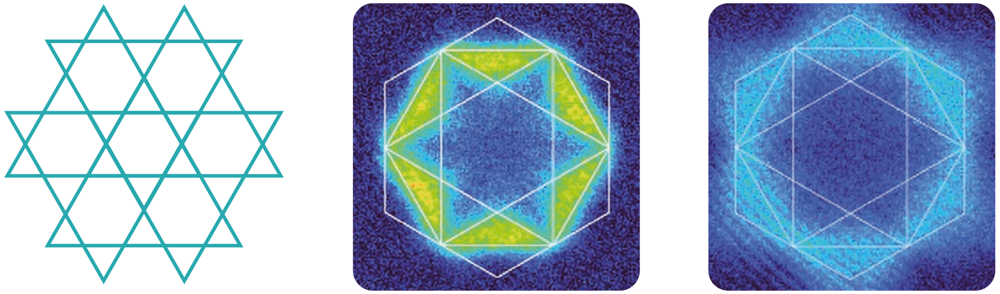


Figure 2. Within the hub, we have realised several different lattice potentials in cold-atom quantum simulators, including triangular lattices and Kagome lattices (image: University of Cambridge)

The Cambridge Team have developed complementary work exploring new lattice geometries, including a triangular lattice in which we can explore atoms in flat bands in regimes where Quantum Monte Carlo calculations are not possible due to sign problems. We also explored systems in quasicrystal potentials, and have developed new techniques that increase lattice programmability using time-varying potentials. This includes the possibility to selectively switch the sign of tunnelling amplitude between lattice sites. The Cambridge team are also developing a new hybrid tweezer-lattice setup, which will open additional future directions for state preparation and lattice control.

Future directions

The path for scaling to 10000 neutral atom qubits in optical tweezer arrays is clear, and the technology is available for this to be done in industry in the course of the next 3 years. At the same time, error correction tools are beginning to be introduced internationally. There remain important challenges around the speed of readout from neutral atom systems, especially for quantum computing in tweezer arrays, and further steps are being taken to improve the flexibility and calibration of architectures for neutral atom quantum simulation. For both quantum computing in tweezer arrays and analogue quantum simulation in optical lattices, a central next stage is to identify or confirm the highest impact potential use cases, and to tailor the next stages of development of the hardware platforms and error reduction schemes to these applications.

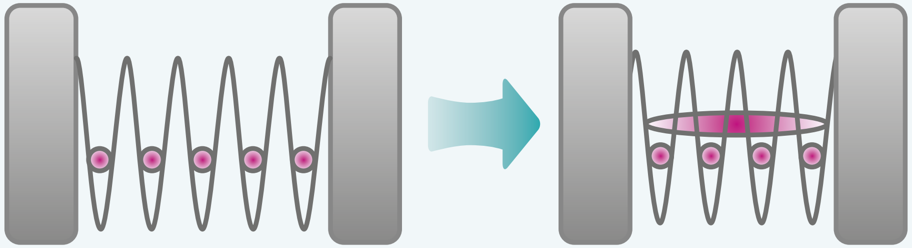
Featured Paper

Commensurate and incommensurate 1D interacting quantum systems

Andrea Di Carli, Christopher Parsonage, Arthur La Rooij, Lennart Koehn, Clemens Ulm,
Callum W. Duncan, Andrew J. Daley, Elmar Haller & Stefan Kuhr,
Nature Communications 15, 474 (2024)

In this paper we have used our control over lattice potentials to dynamically add and subtract available lattice sites for atoms moving in a quantum-gas microscope. This allows us to access commensurate and incommensurate systems in terms of numbers of particles and lattice sites with interacting bosonic Rb atoms. Incommensurate systems are analogous to doped systems in solid-state physics, and when the atoms are strongly interacting, shifting the number of lattice sites from commensurate to incommensurate results in a transition from an insulating state to states that exhibit atom transport and compressibility.

For example, we can prepare a fixed number of atoms in lattice sites (e.g., 5 atoms in 5 lattice sites, as shown in the figure), between two potential barriers. We can then change the position of the barriers such that the number of available lattice sites is reduced while retaining the atom number, leaving one or more particles on average free to move in the strongly interacting system. Our work provides the foundation for preparation of low-entropy states with controlled filling in optical-lattice experiments.



The programmable control developed for cold atoms allows us to change the number of available lattice sites time-dependently, allowing experimentalists to control the filling of particles in sites, analogous to changing the doping in solid-state semiconductor devices. This can be used to drive transitions between insulating states and states with mobile atoms (image from the University of Strathclyde).

Featured Paper

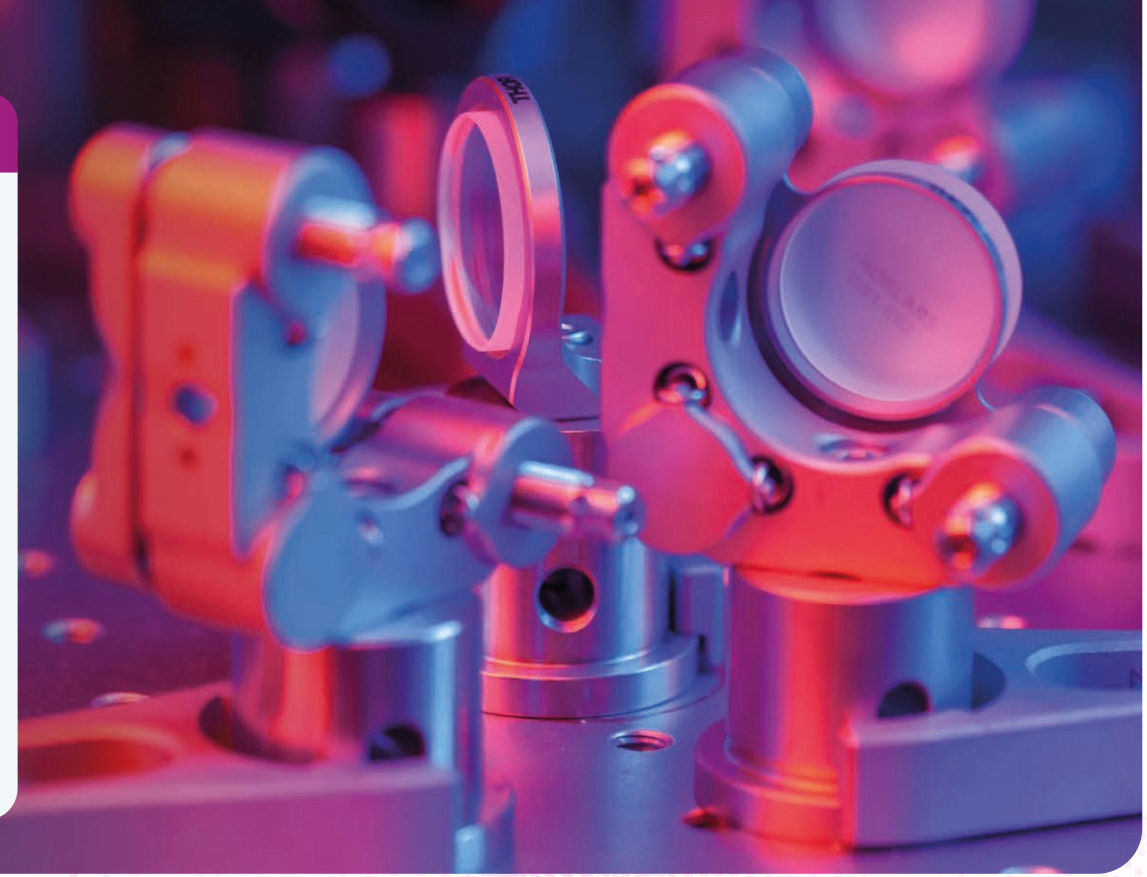
Counterdiabatic Optimized Local Driving

Ieva Čepaitė, Anatoli Polkovnikov, Andrew J. Daley, and Callum W. Duncan,
PRX Quantum 4, 010312

In this paper we combine different ways to speed up adiabatic processes in order to make substantial improvements in techniques for state preparation in analogue quantum simulation. The fundamental idea is to combine the idea of optimal control, which manipulates control fields to steer the dynamics in the minimum allowed time, with shortcuts to adiabaticity, which aim to retain the adiabatic condition upon speed-up. Our method, which we call counterdiabatic optimized local driving (COLD) takes advantage of the strength of both methods and we show that it can result in a substantial improvement when applied to annealing protocols, state preparation schemes, entanglement generation, and population transfer on a lattice. These ideas could also have future applications for quantum annealing or adiabatic quantum computation.

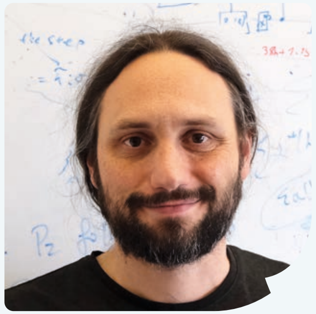
Software and applications research at the Hub

The software activities of the Hub span the following areas: Algorithms and Fundamentals; Applications; Architectures, Control, and Emulation; and Verification, Validation and Benchmarking. Practical quantum advantage, in the near or the long term, will require software activities end-to-end, including theoretical algorithmic analysis (see *Algorithms and Fundamentals*, p.48), practical implementation of specific applications (see *Applications*, p.53), the best use of hardware guided by novel architecture and the use of classical emulation and HPC (see *Architectures, Control and Emulation*, p.44), and finally benchmarking and evaluation of the results (see *Verification, Validation, and Benchmarking*, p.40). Each of the activities is led by a Co-Investigator, and the overall software theme is coordinated by Petros Wallden.



Research Lead

Petros Wallden



Petros Wallden is Reader (Associate Professor) in Quantum Informatics at the School of Informatics at the University of Edinburgh, is Deputy Director of the Quantum Software Lab (QSL), leads the Hub's work on Quantum Software, and is Deputy Co-Chair of the Collaborative Computational Project - Quantum Computing (CCP-QC) network. His current research focuses on quantum algorithms and quantum machine learning, quantum cyber security and verification/benchmarking of quantum computing.

He has published over 50 papers with more than 3100 citations. He is editor for the journal Quantum and the journal Cryptography MDPI, was two times general chair of the IACR international conference on Public Key Cryptography and on several other programme committees.

Verification, Validation & Benchmarking (VVB)

Research Lead

Professor Elham Kashefi

University of Edinburgh

Elham Kashefi is Professor of Quantum Computing at the University of Edinburgh, CNRS Director of Research at Sorbonne Université and Chief Scientist for the UK National Quantum Computing Centre. She has pioneered transdisciplinary research on the structure, behaviour, and interactions of quantum technology, from formal and foundational aspects to industrial use-case delivery. Her research team innovates across a broad range of platforms, with an integrated software research programme delivering impact in quantum computing and quantum networks.

She has received EPSRC Early Career and Established Career Fellowship awards, is a recipient of the Les Margaret Entrepreneur prize, and an elected fellow of the Royal Society of Edinburgh. She co-authored the EU Quantum Software Manifesto, was an Associate Director in the NQIT Hub, and is co-founder and director of the Quantum Software Lab at Edinburgh.

Introduction

The importance of verification, validation and benchmarking is evident as we move forward to an era where quantum hardware scales to sizes greater than that which can be classically simulated and towards the useful quantum advantage point. We are developing a set of tools tailor-made for various hardware to ensure our target applications are implemented correctly. We both certify the device fabrication and also verify the computation, taking into account the noise.

Multiple different approaches to hardware are making progress towards larger and better quantum computing devices. We want to benchmark these devices and, importantly, develop tools that will allow us to benchmark their performance in a scalable way, even for devices that significantly exceed the classical simulation size. Furthermore, applications and algorithms that potentially offer advantages compared to classical techniques will be implemented using such hardware. It is thus of utmost importance that we also develop scalable methods to verify the correctness of such applications, since methods applicable to small instances (for example, that use classical emulation) will no longer be applicable.

The main goal of our work is to provide efficient verification and validation methods that are bespoke for specific applications, resources or hardware and are suitable for:

- NISQ Machines, towards quantum advantage validation
- Quantum Simulation
- Universal FT Quantum Computers

Outcomes

We have explored various directions to benchmark noisy devices, validate the results and verify the computations performed. Our guiding principle in developing these new and scalable tools was close collaboration with the hardware providers, exploring noise models, ensuring our theoretical tools could assist scaling up device fabrication and design, and finally testing our protocols in different hardware. Further research is required to fully cover the gap between some of the theoretical developments and their practical implementations. Below we summarise a few notable results, several of which demonstrate the fruitful interaction between hardware and software.
We have extended the conventional Randomised Benchmarking (RB) techniques, to cover issues relating to both practicality and addressing specific hardware, making RB more targeted to real-world implementations [1]. Our core contribution is based on "light" verification techniques tailored for hardware certification, which simplifies RB by removing the need of an inversion step. Further, it allows for gate synthesis to be able to tailor the scheme for the native gates of a given platform.

To further expand our practical approaches, we also explored a lightweight detection scheme for the errors occurring in the implementation of a target unitary circuit [2]. It considered two cases: one where the target unitary differed from the ideal unitary in only one multi-qubit gate, and one where the unitary consisted of Clifford gates. In both cases the protocol could identify the fault efficiently (with only constant runs of the unitary) and thus was able to correct it. Another lightweight detection scheme was considered in [3], where the performance of the Quantum Fourier Transform (QFT) was benchmarked: a method to verify the QFT performance was given, and the implications of errors from the building block to the algorithms it contained (such as phase estimation) was analysed.

To validate and benchmark quantum computing devices, especially in the context of random quantum circuits and the demonstration of quantum advantage, one approach is to be able to classically simulate sampling from those random outputs that correspond to Born probabilities. Such approaches are based on Monte Carlo sampling. In [4] we introduced two new methods (gate merging and frame optimisation) that significantly reduced the sampling overhead.

Many of our constructions are guided by the verification framework that was developed over the years within the Hub. We revisited this, taking into account all the hardware limitations and requirements, to achieve a recent breakthrough which demonstrates the first practical verification scheme for NISQ devices, completely closing the previously known gaps between theory and implementation [9]. A general framework is now obtained that will further enhance all benchmarking and mitigation schemes built on this approach [10].

Occupying this "in between" space, expanding theoretical toolkits while remaining close to and aware of hardware development, we explored new territories which are particularly important for network architectures for distributed data centres serving multiple clients. In particular we have proposed the first zero-knowledge proof scheme for remote quantum states preparation that will be the key layer for any such hybrid architecture of classical and quantum networks [11]. We also designed a practical verified multipartite delegated computing scheme as the blueprint for quantum computing services in the cloud [12].

Finally, in collaboration with experimental groups, some of the theoretical ideas were implemented. Specifically, in [13] the first hybrid matter-photon implementation of verifiable blind quantum computing was achieved, where the quantum server has a trapped-ion device and the client-side a photonic detection system connected by a fibre-optic quantum network link, and in [14] an adapted fidelity estimation protocol was introduced and implemented on a programmable silicon photonic chip.

Future Directions

The research in benchmarking quantum devices should be systematized and standardized. The metrics that are most scalable and practical should be refined, adding more performance metrics (as quantum computers move to the utility era), extending to different quantum computing systems (such as analogue simulators) and in collaboration with governmental bodies should result in some international standards for evaluating the different quantum hardware. The research in verification of quantum computation should also continue the progress in making such protocols more practical, but also should look into adding verification integrated in implementations, and to extend it in different scenarios and applications.

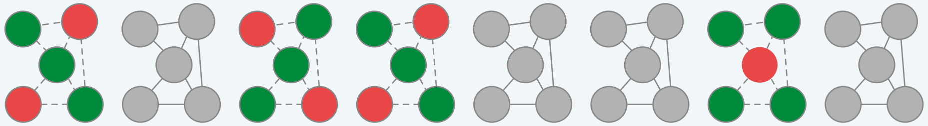
Featured Paper

Verifying BQP Computations on Noisy Devices with Minimal Overhead

Dominik Leichtle, Luka Music, Elham Kashefi, Harold Ollivier. *PRX Quantum 2*, 040302 (2021)

Verifying the correctness of a quantum computation is a very important task that is fundamentally hard to do, once the computation is beyond the scale that can be simulated classically. In the context of delegating a quantum computation to a (generally untrusted) quantum server, the need to be able to verify the computation becomes even more crucial. This scenario is a very likely scenario, as we move to the era that few hardware providers (private or governmental) have direct access to the largest quantum computers, while other clients use them via some cloud services. There exist protocols that can achieve this task in the most general adversarial setting [16]. This protocol, however, requires an overhead compared to the un-verified version of the computation, that makes these algorithms practically impossible. While improvements that reduce this overhead exist [17], the required overhead still makes these protocols less appealing.

In this work [15] the first verifiable blind quantum computation protocol is introduced that has no extra overhead apart from requiring repetitions of the same quantum computation. This means that one can add the verification feature to a blind quantum computing protocol with no extra quantum hardware requirement. Moreover, based on this, one can also construct such verification protocols for noisy devices.



An example of rounds of the proposed protocol. Graphs in gray denote computation rounds, while graphs containing red nodes (traps) and green nodes (dummies) are test rounds. Each qubit is always included in one type of test round. The server remains completely oblivious to the differences between the rounds, which are solely known to the client.

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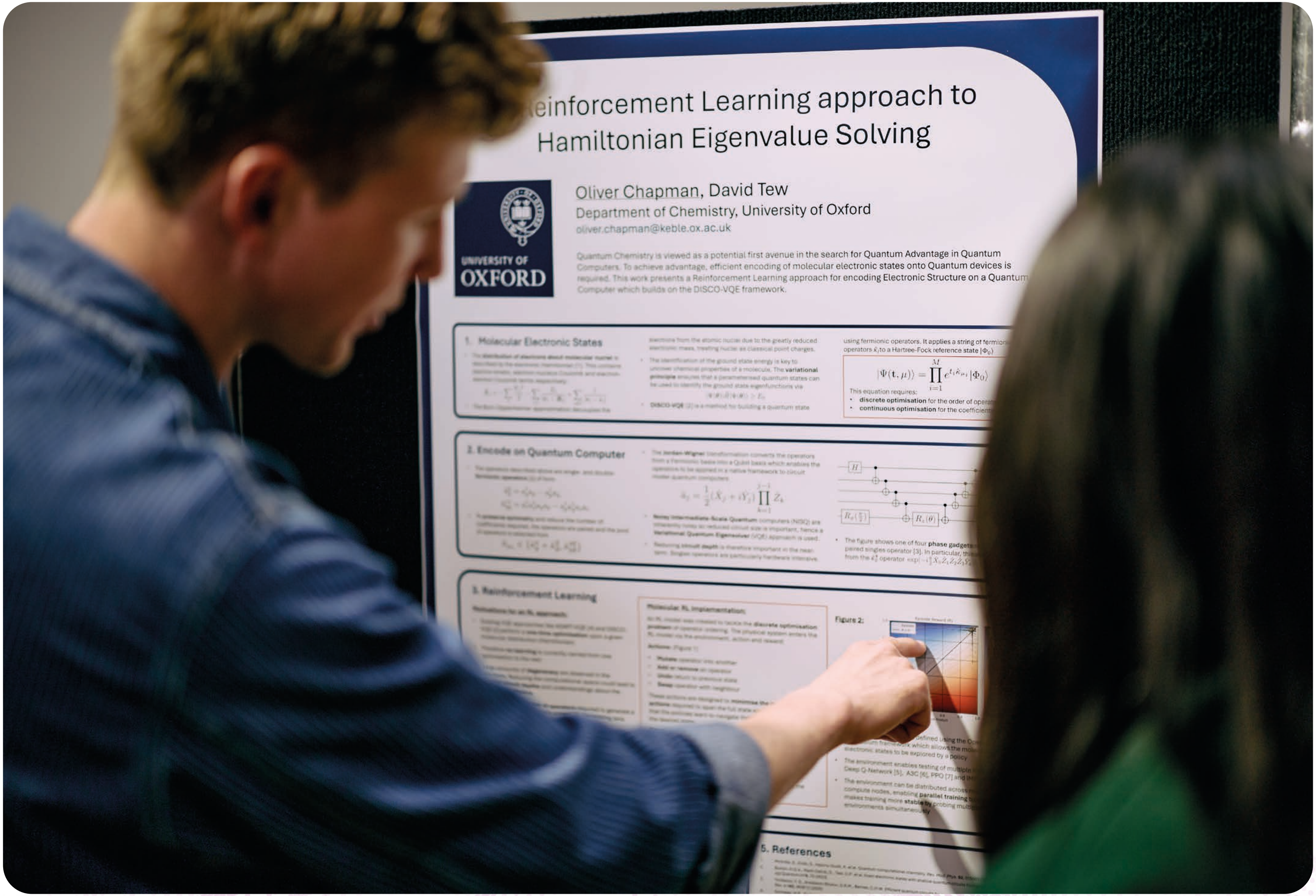

einforcement Learning approach to Hamiltonian Eigenvalue Solving

Oliver Chapman, David Tew
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Quantum Chemistry is viewed as a potential first avenue in the search for Quantum Advantage in Quantum Computers. To achieve advantage, efficient encoding of molecular electronic states onto Quantum devices is required. This work presents a Reinforcement Learning approach for encoding Electronic Structure on a Quantum Computer which builds on the DISCO-VQE framework.

1. Molecular Electronic States

2. Encode on Quantum Computer

3. Reinforcement Learning

5. References

Architectures, Control and Emulation (ACE)

Research Lead

Professor Simon Benjamin
Architectures, Control and Emulation (ACE)

Simon Benjamin is the Professor of Quantum Technologies in the Materials Department at the University of Oxford and recently served as the Deputy Director for Research at the UK's National Centre for Quantum Computation. His team in Oxford looks at aspects of quantum computing, including architectures, fault tolerance, and algorithms that are robust against imperfections in the computer. Simon has held international positions including Visiting Professor at the National University of Singapore, and has been an editor of journals including Science Advances.

In 2017 he co-founded the company Quantum Motion Technologies where he is now Chief Scientific Officer, leading the theory and design effort.

Introduction

The aim of the Hub's work in this area is to support software activities in a way that maximises the performance using imperfect, noisy hardware. The main tools to achieve this are:

Architectures: Understanding the theory of how our qubits should be arranged, the levels of connectivity, the clock speed relevance versus noise, etc. Progress towards fault tolerance (and quantum error correction) is also included here.

Control and Compilation - turning an algorithm from a high-level description into the low-level processes that run on the device. This includes the task of circuit synthesis. Here we also include classical methods to mitigate the effect of noise (quantum error mitigation).

Emulation - using today's classical computers to simulate small quantum computers.

Architectures

We explored different architectures that offer concrete advantages. First, in [1] a multicore architecture was proposed, where multiple quantum cores are connected by an inter-core quantum communication link. This architecture was shown to offer advantage in performing the derangement-circuit error mitigation approach. Second, in [2], looped pipelines enable effective 3D qubit lattices to be embedded in a strictly 2D device. This is important since, on the one hand, many devices have naturally 2D physical layouts and, on the other hand, the 3D qubit lattices enable a variety of improvements including certain quantum error mitigation methods as well as certain quantum error correction codes, suggesting that this work will offer advantages both in the NISQ and in the FT era.

Furthermore, we have worked on different aspects of quantum error correction. Firstly, in [3] we expanded the surface code to accommodate temporary or permanent defects, by using an adaptive surface code. The result demonstrated that despite the defects, the threshold was almost not affected. Secondly, in [4] new Low-Density-Parity-Check (LDPC) codes are introduced, that are specifically designed for modular architectures. This opens the possibility to construct codes with better parameters in practice. Finally, in [5] we considered the decoding part of QECC. This is one of the practical bottlenecks for scaling quantum error correction. The proposed decoder has extra (strict) locality constraints, something that can have benefits including speed, layout and robustness. We demonstrated that this locality does not come with disadvantages since it largely maintains the merits of the "vanilla" union-find decoder.

Control and Compilation

Trying to maximise the use of limited access to a quantum device, one can try to use simpler resources to achieve more complicated tasks, using classical post-processing. This theme appears also in other work packages and outputs (e.g., in verification methods, in near-term algorithms and in some applications). Here we specifically contributed to different aspects of the research in quantum error mitigation. In [6] we provided a state-of-the-art review of this expanding and crucial topic for finding near-term applications. In a recent breakthrough [7] it was shown that multiple quantum computers can work on the same problem in parallel and then, at the end of the computation, their outputs are used to effectively verify each other, via a so-called 'derangement circuit'. The approach may be suitable for relatively near-term quantum technology as it only needs a few interlinked quantum processors. In [8] a method that uses symmetry and randomisation simplifies the error channels and leads to improved sample-complexity of matrix-inversion, improved noise-estimation, and improved predictability of the performance of noise circuits. This was tested in simulation and in superconducting real hardware. In [9] a method was given that uses multiple runs of imperfect measurements to recover an "ideal" measurement with average error that drops exponentially with the number of imperfect measurements. In similar spirit, in [10] continuous quantum rotation angles are derived via interpolation using just three gate settings, and only with classical post-processing. Finally, in [11] the readout error was mitigated by a new method that removes biases in the readout errors, allowing a general error model to be built with far fewer calibration measurements.

Emulation

Using classical emulators can be very beneficial, for example in the development of algorithms, error mitigation methods, benchmarking, and understanding the virtues and limitations of hardware and different architectures. The ideal simulations can give indications of the performance of noiseless (FT) quantum algorithms as, for example, in [12] [13]. Noisy simulations, on the other hand, can be a tool to test a variety of methods as mentioned earlier, but also test our assumptions about the noise model and physical mechanisms of errors in real devices. It is of utmost importance that such emulators become available open source and in an approachable way to different communities. In the Hub we have developed a family of such emulators called QuEST (Quantum Exact Simulation Toolkit). It is a C and C++ based simulation framework which supports a rich set of operations like Pauli gadgets, multi-qubit general unitaries, density matrices, and general Kraus maps. QuESTlink integrates these in Mathematica and pyQuEST gives Python programmers access to this resource. These emulators can run on local (e.g., laptop), multi-core, GPU, and distributed systems seamlessly. QuESTlink can even use remote hardware to perform simulations, with the results accessible within Mathematica.

To include noise, in [14] we introduced the Virtual Quantum Device (VQD) platform. This is a system based on the QuEST quantum emulator. Using VQDs, non-expert users can emulate specific quantum computers with detailed error models, bespoke gate sets and connectivity. Five families of VQDs corresponding to trapped ions, nitrogen-vacancy centres, neutral atom arrays, silicon quantum dot spins, and superconducting devices were created and explored, with close collaboration across our hardware work packages helping to enable this. The VQD platform offers researchers the ability to rapidly explore algorithms and protocols in a realistic setting; meanwhile, hardware experts can create their own VQDs to compare with their experiments.

Finally, in [15] the a-priori difficult task of distributing a simulation of a quantum algorithm to multiple classical cores, as done in high-performance computing, was shown to offer advantages even in simple models of distribution. For example, it offered better efficiency for Pauli gadgets, many-controlled many-target general unitaries, density matrices, general decoherence channels, and partial traces.

Future directions

Research in this domain will become one of the most important bottlenecks in reaching quantum utility and achieving the national mission of 1 trillion quantum operations. Specifically, research in quantum error correction, being in the theory of codes, practicality of decoding, or on the practicality and compatibility with different platforms and architectures, will be essential in any attempt to succeed in these tasks. As the field matures, other parts/layers of the full quantum stack will also become important, and we should aim that abstractions and automation will occur as in classical computing, enabling the more efficient integration of researcher from applications, algorithms, all the way to the hardware research, without the necessity that everyone understands all the different levels in the same depth.

QuEST and QuESTlink can run on local, multi-core, GPU and distributed systems seamlessly. QuESTlink can even use remote hardware to perform simulations, with the results accessible within Mathematica.

Featured Paper

Grid-based methods for chemistry simulations on a quantum computer

Chan HHS, Meister R, Jones T, Tew DP, Benjamin SC,
Science Advances 9 (9), eabo7484Science (2023)

First-quantized, grid-based methods for chemistry modeling are a natural and elegant fit for quantum computers. However, it is infeasible to use today's quantum prototypes to explore the power of this approach because it requires a substantial number of near-perfect qubits. Here, we use exactly emulated quantum computers with up to 36 qubits to execute deep yet resource-frugal algorithms that model 2D and 3D atoms with single and paired particles. A range of tasks is explored, from ground state preparation and energy estimation to the dynamics of scattering and ionization; we evaluate various methods within the split-operator QFT (SO-QFT) Hamiltonian simulation paradigm, including protocols previously described in theoretical papers and our own techniques.

While we identify certain restrictions and caveats, generally, the grid-based method is found to perform very well; our results are consistent with the view that first-quantized paradigms will be dominant from the early fault-tolerant quantum computing era onward.

An ammonia molecule depicted in a grid-based model.

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Professor Myungshik Kim's Group at Imperial College London

Algorithms & Fundamentals

Research Lead

Professor Noah Linden

Algorithms and Fundamentals

Noah Linden is Professor of Theoretical Physics and Director of the Bristol Quantum Information Institute which is the umbrella organisation for all quantum information and technology activities at the University of Bristol.

He has made major contributions to quantum information theory and quantum computation, including work on the foundations of quantum computation, quantum computational architectures, non-locality, and entanglement.

Introduction

The Hub's work in this area is, on the one hand, to look into the future of the field in order to provide answers to long-term questions around the power and nature of quantum computation and information and to design new algorithms for key mathematical and physical problems and, on the other hand, to develop techniques/algorithms for near-term hardware and examine their limitations. Our research has given major contributions to these topics and we report here on some indicative results.

Algorithms and limitations for near-term (NISQ) hardware

Variational quantum algorithms (VQAs), which use a classical optimizer to train a parameterized quantum circuit, have emerged as a leading strategy to address the challenges of limited numbers of qubits and noise processes that limit circuit depth. VQAs have now been proposed for almost all applications that researchers have envisaged for quantum computers, and they appear to be the best hope for obtaining quantum advantage. Nevertheless, challenges remain, including the trainability, accuracy and efficiency of VQAs. A team of leading international collaborators, including the Hub's Simon Benjamin, produced a major review of VQAs that appeared in Nature Physics [1].

Looking specifically at optimisation with focus on the Quantum Approximate Optimisation Algorithm (QAOA), one of the challenges to obtain quantum advantage comes from the classical optimisation part of the algorithm, including: cost landscapes with many local minima, cost landscapes become that exponentially-fast become vanishing (the so-called barren plateaux), optimisers that takes too long to converge or converge to suboptimal solutions. Our research made several proposals that bring us closer to overcoming those challenges. In [2] we considered the MaxCut problem and instead of starting QAOA at random inputs, we proposed the use of graph neural networks for a "warm-start" method and demonstrated that it practically performs better than random initialisations, while the method also proves to have good generalisation, i.e. the performance enhancement was maintained on different problems and different sizes, a feature hard to achieve in other warm-start approaches. This indicates that this method could prove valuable for achieving quantum advantage, as this is expected to happen at sizes that most warm-start methods cannot be applied directly, and our generalisation property would be essential. In [3] another warm-start method was introduced where we used simulated annealing of the efficiently simulable Clifford parameter points as a pre-optimisation to find a low energy initial condition. In [4] we proposed the use of an evolving objective function, that could avoid local minima and enhance the probabilities of success (in some instances tenfold) and was demonstrated in MaxCut, Number Partitioning and Portfolio Optimisation examples. In [5] we proposed a new optimiser that uses information of the geometry of the quantum state space, and specifically information about how small changes in parameters affect it. Previous proposals were based on the Quantum Natural Gradient (QNG) [6], that, while theoretically offering a more accurate and faster optimiser, requires quadratically more quantum state preparations than vanilla gradient-descent approaches.

Our proposal was based on an approximation of the QNG that uses the classical Fisher Information Matrix and requires quadratically less quantum-state preparations. This geometry-based approach requires the same resources with simpler methods, while maintaining the advantages offered by the QNG.

In [7] we proposed a new heuristic to tackle combinatorial optimisation problems that is inspired by the Hamiltonian for optimal state-transfer. We find this approach results in a better approximation ratio than the QAOA at lowest depth for most problem instances considered, while utilising comparable resources. Finally, in [8] we proposed a new method that uses concepts from adiabatic quantum computing, but brings them to the circuit and specifically NISQ model. We first demonstrated how, starting from a ground state prepared in a parameterised quantum circuit (PQC), we can obtain a new ground state, in the form of new parameters for the parameterised circuit, for a Hamiltonian that is slightly perturbed. This was done by solving a system of constrained linear equations. Using this method, we mimic a discrete version of adiabatic quantum computing, where we start with the ground state of a known Hamiltonian (obtained via some parameters of a PQC) and then iteratively perturb it to obtain the final ground state of the desired Hamiltonian. This method appears to perform better, avoiding barren plateaux, and could be viewed as a form of a warm-start method (where the subsequent algorithm is also altered).

One of the promises for quantum advantage is for sampling tasks such as the Boson Sampling (BS) – both in its vanilla version and in the continuous-variables Gaussian Boson Sampling (GBS) case. One of the first quantum advantage experimental claims came from a GBS experiment performed by a team from the University of Science and Technology, China. In [9], we exploited the fact that the detectors could only distinguish zero from non-zero photons and constructed a classical simulation of GBS that runs 1 billion times faster, significantly moving the boundary of what can and what cannot be classically achieved. In [10] we considered the vanilla BS and added non-linearities. We then demonstrated that these non-linearities make the sampling distribution harder to classically simulate, making BS more robust to noise.

Another very promising approach for NISQ devices is the use of Quantum Machine Learning (QML) and specifically the use of a PQC as a form of a quantum neural network. While there is a big volume of research on this topic, there are very few results showing the potential and limitations of these approaches theoretically. A lot of the promise comes from the belief that QML offers more expressive neural networks. In [11] we showed that a large class of these models, where the encoding used is the "Hamiltonian-encoding", cannot offer advantage. This was shown by constructing a classical method using Random Fourier Features that can approximate well many of these families that use Hamiltonian encoding. The result highlights the limitations of QML, but also enables us to find encodings that do not satisfy those criteria and may potentially offer advantage.

Algorithms and limitations for long-term (FT) hardware

The first theme of this research is the complexity (difficulty) of key physical and mathematical questions. The difficulty can be quantified in terms of many figures of merit, such as computational resources/running time, or numbers of times that a function is queried, or rounds of communication between parties. In "Computational Complexity of the Ground State Energy Density Problem" [12], the complexity of finding the ground state energy density (GSED) of a local Hamiltonian on a lattice in the thermodynamic limit of infinite lattice size was analysed. The paper made significant impact in the theoretical computer science community as it was a plenary talk at QIP, the leading international conference in quantum information, and was accepted at the *Symposium on the Theory of Computing (STOC) 2022*, one of the two major conferences in theoretical computer science. This is formulated rigorously as a function problem, in which one requests an estimate of the ground state energy density to some specified precision; and as an equivalent promise problem, GSED, in which we ask whether the ground state energy density is above or below specified thresholds. Hardness of this problem for a complexity class implies that the solutions to all problems in the class are encoded in this single number (analogous to Chaitin's constant in computability theory). This captures computationally the type of question most encountered in condensed matter physics, which is typically concerned with the physical properties of a single Hamiltonian in the thermodynamic limit, and the paper gives rigorous bounds on the computational resources required.

In [13] the hardness of evaluating a function of a Hermitian matrix using classical and quantum resources is examined. This is quantified by the number of queries/evaluations one requires to make to the function. The paper proves that the quantum and classical separation is exponential for any continuous function of sparse Hermitian matrices, and implies the optimality of implementing smooth functions of sparse Hermitian matrices by quantum singular value transformation. Proven exponential separations are very important, since they demonstrate the true potential for quantum computing and motivate the development of hardware towards the fault tolerant era.

In [14] we show that quantum computers have provable polynomial and exponential speedups in terms of communication complexity for some fundamental linear algebra problems if there is no restriction on the rank. We investigate these two problems in two-party and multiparty models, propose near-optimal quantum protocols and prove quantum/classical lower bounds. In this process, we propose an efficient quantum protocol for quantum singular value transformation, which is a powerful technique for designing quantum algorithms. This will be helpful in developing efficient quantum protocols for many other problems.

Beyond the complexity, we researched general tools to improve performance. In [15] we consider the majority vote, a basic method for amplifying correct outcomes that is widely used in computer science and beyond. While it can amplify the correctness of a quantum device with classical output, the analogous procedure for quantum output is not known. We introduced a quantum majority vote concept and showed that under the condition that 2/3 of the inputs are in the majority state, one can recover the desired target state with fidelity that approaches unity as the number of copies increases. A more general problem that involves the evaluation of a Boolean function is shown to have an optimal quantum algorithm that is a generalisation of the quantum majority vote, and the performance is quantified.

Finally, we considered some limitations of certain quantum computational models – those that involve operations performed on some fixed resourceful quantum state, such as magic state injection and measurement-based approaches. In [16] a framework that incorporates both cases is introduced and focuses on the role of coherence (or superposition) in this context, as exemplified through the Hadamard gate. It is proven that given access to incoherent unitaries, classical control, computational basis measurements, and any resourceful ancillary state (of arbitrary dimension), it is not possible to implement any coherent unitary (e.g., Hadamard) exactly with non-zero probability. The approximate case is also considered by providing lower bounds for the induced trace distance between the above operations and n Hadamard gates. To demonstrate the stability of this result, this is then extended to a similar no-go result for the case of using k Hadamard gates to exactly implement $n>k$ Hadamard gates.

Overlap with other software work packages

Since this work package covers the theory of quantum computing, there are results that belong to some other specific task (verification, quantum error mitigation, architecture) that are better fitted and reported in those packages, that still constitute contributions that would belong here too. For example, theoretical contributions that are reported elsewhere include [17][18][19].

Future directions

The UK national quantum mission aims for quantum computers capable of running 1 trillion operations and supporting applications that provide benefits well in excess of classical supercomputers across key sectors of the economy. To be able to support applications with utility with this number of quantum operations, progress in quantum algorithms is essential. The two main directions that seem more promising for that stage are: firstly develop further NISQ approaches considering the case where the logical errors are low (but non-zero) following a partial quantum error correction, secondly reduce the overhead for fault-tolerant quantum algorithms, focusing on optimizing the resources required, that lead to algorithms suitable for the "early fault-tolerant" era.

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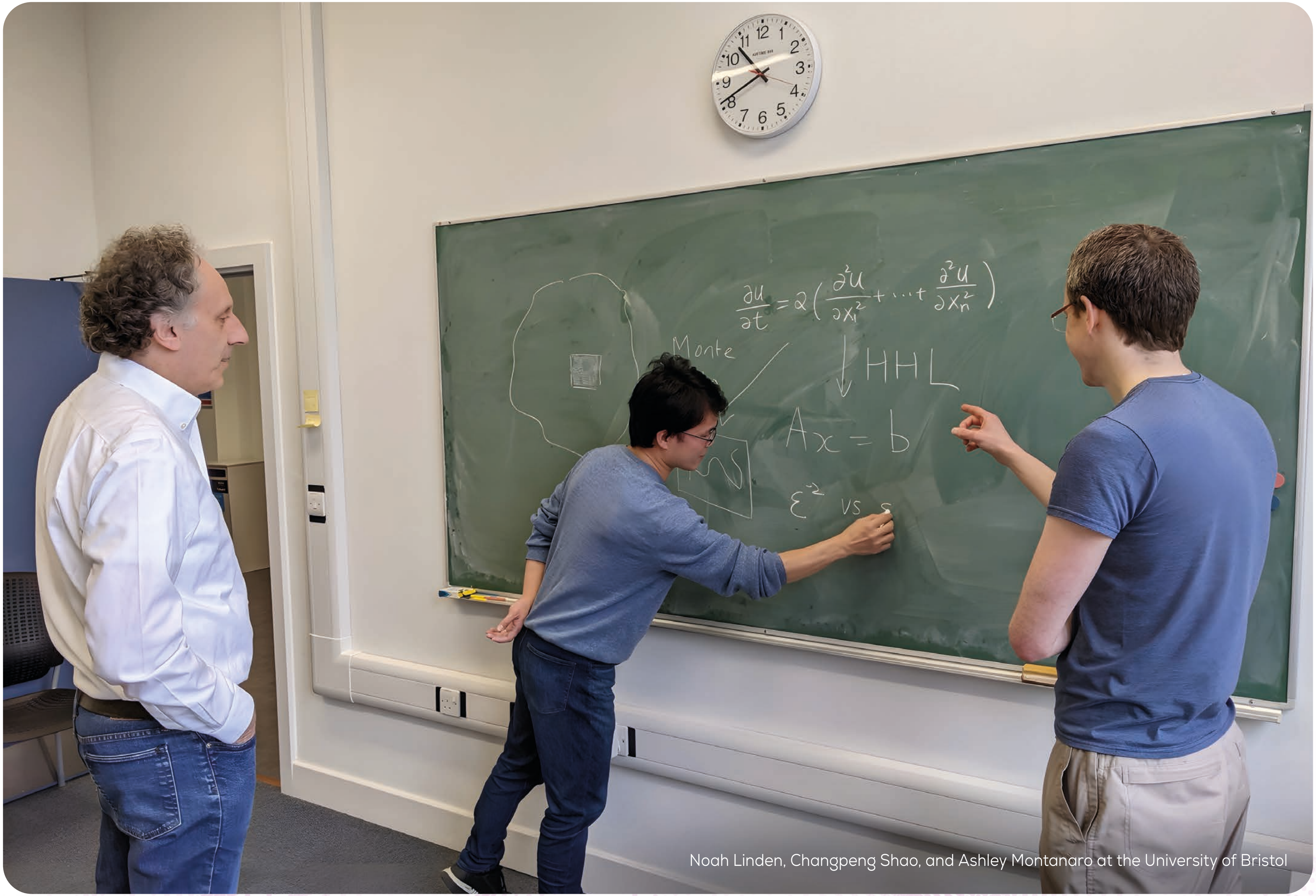


Noah Linden, Changpeng Shao, and Ashley Montanaro at the University of Bristol

Featured Paper

Quantum vs. classical algorithms for solving the heat equation

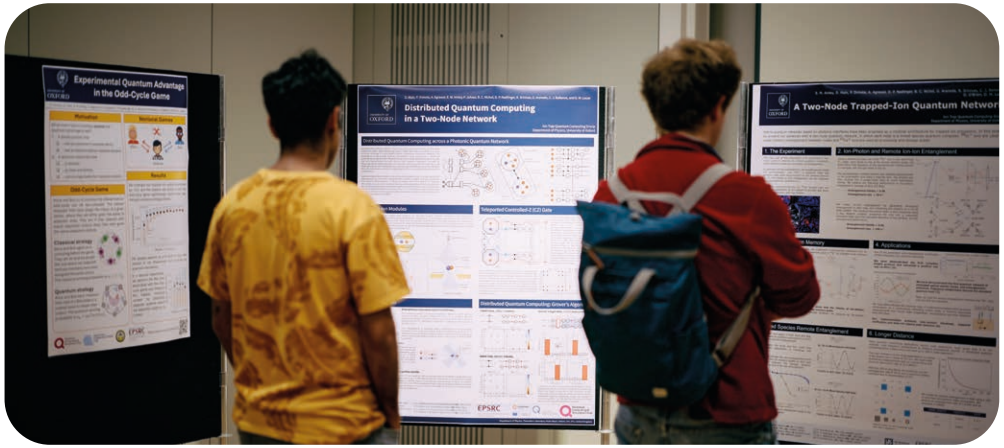
Linden, Montanaro and Shao, *Commun. Math. Phys.* 395, 601–641 (2022)

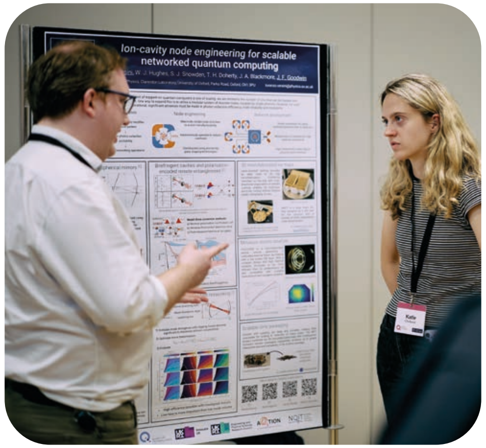
Quantum computers have been predicted to outperform classical ones for solving partial differential equations (PDEs), perhaps exponentially. Hub researchers Noah Linden, Ashley Montanaro, and Changpeng Shao's paper *"Quantum vs. classical algorithms for solving the heat equation"* [3], has now appeared in *Communications in Mathematical Physics*. The paper considers the prototypical PDE–the heat equation in a rectangular region–and compares in detail the complexities of ten classical and quantum algorithms for solving it, in the sense of approximately computing the amount of heat in a given region.

It is found that, for spatial dimension greater than two, there is an at most quadratic quantum speedup in terms of the allowable error using an approach based on applying amplitude estimation to an accelerated classical random walk.

However, the famous alternative approach based on a quantum algorithm for linear equations (due to Harrow, Hasidim and Lloyd) is never faster than the best classical algorithms. This latter fact is significant since it means, in particular, that the hoped-for exponential improvement of quantum over classical for this canonical linear PDE does not occur.

Academic research, as demonstrated in our Hub, needs to provide provable performance of quantum computing, highlighting both the cases where we do get advantage but also, very importantly, the limitations where we do not get the anticipated exponential advantage.





Applications

Research Lead

Professor Dan Browne

Applications

Dan Browne is Professor of Physics at University College London. He has been active in quantum computing research for over 20 years, and has broad research interests. He is known for his work on measurement-based quantum computing and photonic quantum computing, and his current research focuses on both the capabilities of near-term Noisy Intermediate-Scale Quantum (NISQ) Computers and large-scale fault tolerant quantum computers.

Introduction

Quantum computers have the potential to bring huge advantages to a wide variety of real-world applications. For example, the simulation of physical systems can enable a virtual quantum laboratory aiding research in chemistry, material science and biochemistry, and replacing slow and unreliable physical experiments. This could rapidly accelerate the discovery of new materials with exotic properties or new drugs. There are also promising potential applications in industry sectors from finance, where asset pricing is a very computationally challenging problem, to logistics, where difficult optimisation problems are faced in many industries such as manufacturing and shipping.

There remain, however, many open questions in the potential performance and hardware requirements for these applications. For example, is full error correction and fault tolerance required, potentially increasing the size of quantum computer needed by factors of thousands, or is it possible to achieve the computation with a more modest quantum circuit, for example one with a low number of quantum gates, minimizing the impact of noise with error mitigation strategies rather than full error correction.

The goal of the Hub's research into quantum computing applications is to study the requirements and performance of promising applications for near to medium-term quantum computers. The research to make this possible includes both application-targeted approaches and improvements in the methods that are applicable to many applications. Here we focus on the former, while the latter have already been reported in the Algorithms and Fundamentals section. Our research has targeted applications in: chemistry, cryptography, machine learning and big data, known NP problems, and practical amplitude estimation.

Chemistry

In [1] first-quantised, grid-based methods for simulating chemical systems were considered. This approach requires a small number of near-perfect qubits, and could be a good candidate for early FT computing. In this work many such simulations were tested using the QuEST emulator (see page 42) with up to 36 qubits, and the results suggested were promising for early adoption. The simulations included: split-operator QFT techniques to 2D and 3D systems with single and paired particles and the dynamics in the presence of strong external fields as well as the dynamics of scattering; creation and exploration of nonunitary wave packet attenuation approaches; introduction of an augmented split-operator method; 2D simulation of ground and first excited state of Hydrogen and simulation of Helium in real space; enhanced state-preparation methods; and estimation of quantum resources for simulations beyond the reach of emulation.

Cryptography

There are many quantum computing applications within the field of cryptography. Perhaps the most well-known is the use of Shor's algorithm to factor or solve the discrete logarithm problem, and thus compromise the security of the majority of currently used cryptosystems including RSA, DSA, and ECDSA. To mitigate this, classical cryptography has moved to using different techniques, believed to be hard for quantum computers, the so-called post-quantum (or quantum-safe) cryptography. It is still of utmost importance to examine the optimal quantum attacks on those new cryptosystems, not only to establish that there are no efficient quantum attacks, but to also ensure that the security parameters chosen (e.g. key sizes) for the new standards for cryptography are such that they offer the same levels of security as their predecessors did. [2] considers the Noisy Binary Linear Problem (NBLP) that had been considered for post-quantum cryptographic primitives. In this work, we presented a complete analysis of the quantum solvability of the NBLP by considering the entire algorithm process and we show that the cost of solving the NBLP can be polynomial in the problem size, at the expense of exponentially increasing logical qubits.

In [3] we consider the Shortest-Vector Problem (SVP) and estimate the exact resources that would be required if one were to use the "obvious" quantum attack that exploits Grover's search algorithm. We also discuss how this naïve approach can be combined with classical state-of-the-art SVP solvers to slightly improve classical attacks. In [4] we consider the query complexity of multi-solution Bernoulli searches, a problem that we show has direct implications in the security of Proof-of-Work blockchains and specifically to the Bitcoin. We show that the Bitcoin remains secure with some changes in what is considered as "honest majority", and demonstrate that the waiting time does not need to increase if this condition is met.

There are more applications that quantum computing and quantum information processing can have in the field of cryptography. In [5] a framework (available as an open-source repository - the Quantum Protocol Zoo) for the unification and standardization of quantum network protocols is presented, making their realization easier and expanding their use cases to a broader range of communities interested in quantum technologies.

Differential privacy provides a theoretical framework for processing a dataset about N users, in a way that the output reveals minimal information about any single user. Such notion of privacy is usually ensured by noise-adding mechanisms and amplified by several processes, including subsampling, shuffling, iteration, mixing and diffusion. In [6] we provide privacy amplification bounds for quantum and quantum-inspired algorithms. In particular, we show that algorithms running on quantum encoding of a classical dataset or the outcomes of quantum-inspired classical sampling, amplify differential privacy. Moreover, we prove that a quantum version of differential privacy is amplified by the composition of quantum channels, provided that they satisfy some mixing conditions.

Machine learning and big data

Quantum autoencoders serve as efficient means for quantum data compression. In [7] we propose and demonstrate their use to reduce resource costs for quantum teleportation of subspaces in high-dimensional systems. We use a quantum autoencoder in a compress-teleport-decompress manner and report the first demonstration with qutrits using an integrated photonic platform for future scalability. Subspace encodings hold great potential as they support enhanced noise robustness and increased coherence. Laying the groundwork for machine learning techniques in quantum systems, our scheme opens previously unidentified paths toward high-dimensional quantum computing and networking.

Current quantum hardware prohibits any direct use of large classical datasets. Coresets allow for a succinct description of these large datasets and their solution in a computational task is competitive with the solution on the original dataset. The method of combining coresets with small quantum computers to solve a given task that requires a large number of data points was first introduced by Harrow. In [8] we apply the coreset method in three different well-studied classical machine learning problems, namely Divisive Clustering, 3-means Clustering, and Gaussian Mixture Model Clustering. We provide a Hamiltonian formulation of the aforementioned problems for which the number of qubits scales linearly with the size of the coreset. We then evaluate how the variational quantum eigensolver (VQE) performs on these problems and demonstrate the practical efficiency of coresets when used along with a small quantum computer performing noiseless simulations of instances up to 25 qubits.

NP problems

In [9] we made heuristic predictions on the performance of continuous-time quantum walks for MaxCut, by exploiting the link between time-independent Hamiltonians and thermalisation. MaxCut (finding a bi-partition of a graph that cuts the greatest number of edges) is a problem that is used as an example for variational quantum algorithms due to its simple mapping to Ising Hamiltonians, but it also has importance on its own in, for example, Flow Networks including circuit optimisation (VLSI design), computer vision and others. Our method is then extended to the time-dependent setting with multi-stage quantum walks and Floquet systems. The approach we followed provides a novel way of understanding the role of unitary dynamics in tackling combinatorial optimisation problems with continuous-time quantum algorithms. In [10] we considered another well studied NP problem in the quantum setting, namely the Max 2-SAT. We numerically analyse the relative hardness of Max 2-SAT problem instances for various continuous-time quantum algorithms and a comparable classical algorithm. Our results show a widening range of hardness of randomly generated instances as the problem size is increased, which demonstrates both the difference in the distribution of hardness at small sizes and the value of a portfolio approach that can reduce the number of extremely hard instances. We identify specific weaknesses of these quantum algorithms that can be overcome with a portfolio approach, such as their inability to efficiently solve satisfiable instances (which is easy classically).

Practical amplitude estimation

The quantum algorithm for amplitude estimation was first proposed in the 1990s, but in a form which is extremely difficult to accomplish without a large-scale fault-tolerant quantum computer. This algorithm is a core component of algorithms with many applications, for example, in asset pricing in finance, and data analysis via quantum machine learning. Recently, it was realised that the algorithm could be simplified and achieved with much more modest quantum computational resources. In [11] we developed an improved form of the algorithm, and studied its performance on medium-term quantum computers where the size of the computation that can be performed is limited by noise and error.

Future Directions

In the last few years, as shown in the outcomes of our Hub, quantum scientists have started focusing on use cases with end-user interest and trying to demonstrate that quantum approaches are viable. Going forward, towards the early fault-tolerant era, interaction between the quantum algorithms research, and classical experts in each use case, need to integrate further, researching more and more applications with a great societal impact, such as in healthcare and life sciences, in energy, in transport and manufacturing.

The quantum machinery and approaches to enhance classical solutions are increasing, and it becomes essential to construct bespoke solutions, that require understanding of all sides (classical solutions, quantum algorithms, hardware constraints, implementation hurdles, benchmarking of solution) that maximise the resources and bring the quantum utility within the targets of our national quantum strategy.

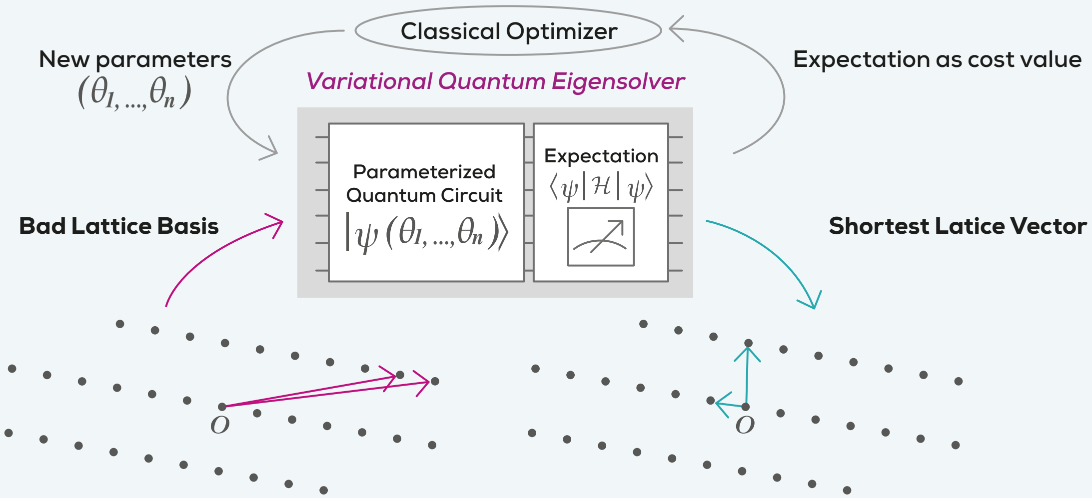
Featured Paper

Variational quantum solutions to the Shortest Vector Problem

M. R. Albrecht, M. Prokop, Y. Shen, P. Wallden, Quantum 7, 933 (2023)

Existing encryption schemes, used in everyday life, are based on the assumption that factoring a large number is hard. Due to Shor's quantum algorithm, that can solve this problem using a large fault-tolerant quantum computer efficiently, the security of all these communications will get compromised. Because of this threat, alternative encryption schemes are being considered, where their security relies on assumptions about the hardness of other mathematical problems that are believed to be hard for quantum computers. The most prominent such problem is the Shortest-Vector-Problem (SVP), where three of the four algorithms recently announced to be standardised by the National Institute for Standards and Technology (NIST) are based on lattice constructions and essentially this problem. While SVP is strongly believed to be hard for quantum computers, it is not clear how hard it is, or else, what is the best that a quantum computer (fault-tolerant or not) can do in solving this problem.

In our work we examine how to solve the SVP using quantum computers and algorithms that can be run on exiting or near-term, imperfect, devices. We significantly reduce the number of qubits required to run such algorithms by providing bounds on the coefficients of the shortest-vector and by excluding the zero vector in a more efficient way. We are able to solve SVP for dimension 28 in a simulation, and we extrapolate that the classical record for SVP can be tackled using quantum computers with around one thousand qubits. We note, however, that our results do not invalidate any security claims made by post-quantum candidates as part of current standardisation efforts to replace cryptographic algorithms, since the time-complexity of our approach remains exponential and the chosen security parameters are far beyond what could be solved by our approach.



On the left side is the input to the algorithm, a "bad" basis. This is the input to the Variational Quantum Eigensolver (top), where one uses Parametrised Quantum Circuits to prepare candidate states, their energy is calculated and a classical optimisation loop runs until parameters that minimise the cost are found. Then on the right side is the output of the algorithm, a "good" basis that can be used to return the shortest vector of the lattice.

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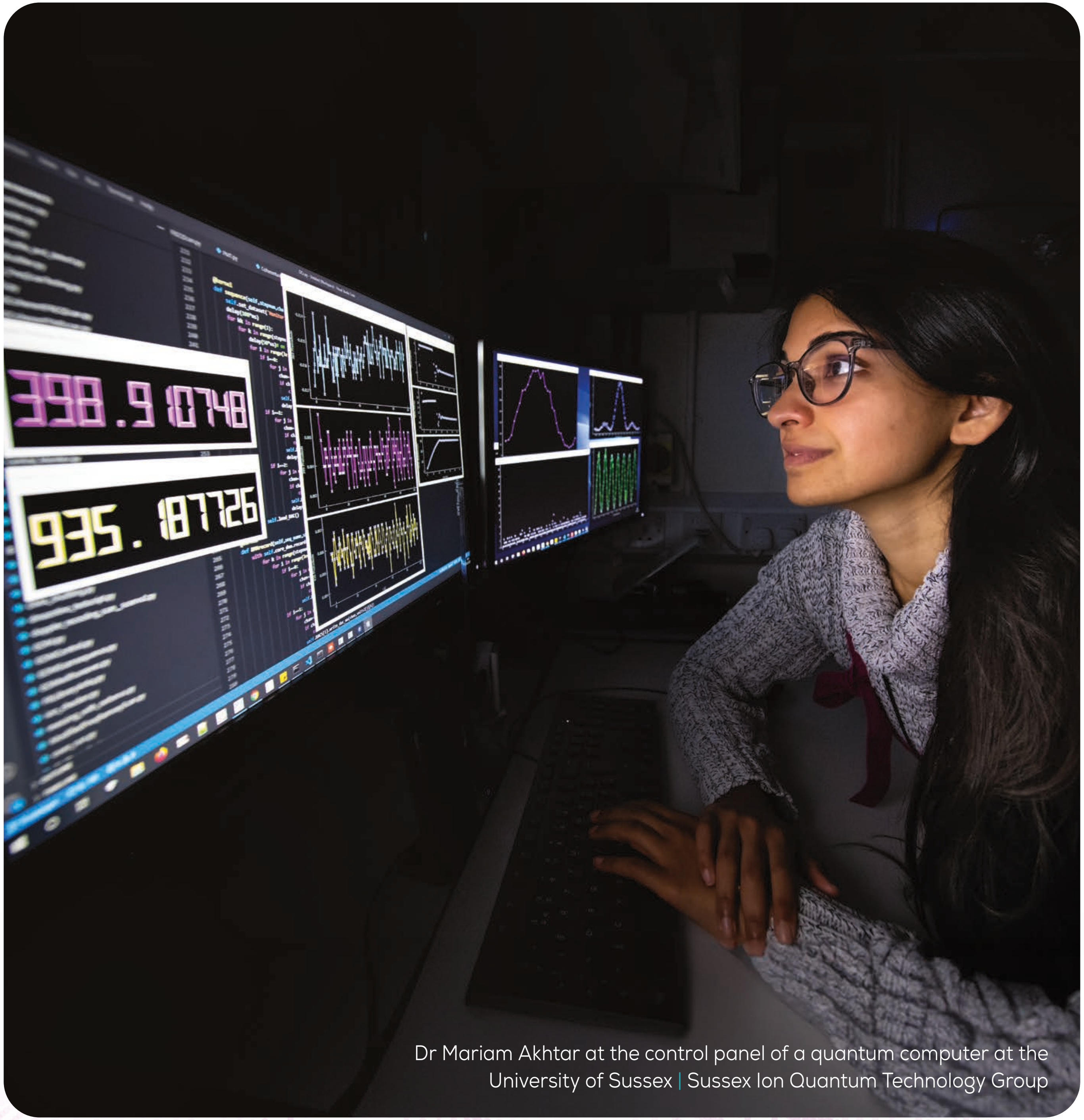


Dr Mariam Akhtar at the control panel of a quantum computer at the University of Sussex | Sussex Ion Quantum Technology Group

Commercial & Industrial Impact

Over the ten years of the National Quantum Technologies Programme, the NQIT Hub and the QCS Hub have been involved in several spin-out companies, either where the founders of the company were co-investigators in the Hub, or where the company uses results from the Hub, or where the company partnered with the Hub's research or user engagement activities.

Notable examples of spin-outs over the ten years of Hub activity in these categories are Oxford Quantum Circuits, Quantum Motion Technology, Universal Quantum, ORCA Computing, Oxford Ionics, and Quantum Dice. A measure of success of this programme is that these spin-outs alone have raised almost four times the EPSRC funding of the Quantum Computing Hubs.

Company Name	Date Founded	First publicly-disclosed funding round	Money Raised (£)[1]
OQC	2017	2022	117,900,000
Quantum Motion	2017	2020	50,000,000
Universal Quantum	2018	2020	3,600,000
Oxford HighQ	2018	2018	2,100,000
Oxford Ionics	2019	2020	34,700,000
Quantum Dice	2020	2021	2,000,000
ORCA	2019	2022	12,000,000
QuantrolOx	2021	2022	4,400,000
Total			**226,700,000**

1 – Source: crunchbase.com

Intellectual Property

The following lists patents granted or applied for that are related to QCS Hub research.

1. Random Number Generator (Walmsley, Nunn, Kolthammer, Garces, Drahi, patent WO2018087516)
2. Quantum Random Number Generator (Zajac, Smith, patent WO2023073344)
3. System for Quantum Information Processing (Morley, Smith, patent WO2024009096)
4. De-Multiplexer And Method Of Separating Modes Of Electromagnetic Radiation (Nunn, Walmsley, Raymer, Saunders, Brecht, patent WO2019116019)
5. Multiplexer for multiplexing signals from a plurality of readout resonators, and a circuit QED apparatus (Bakr, Leek, application PCT/GB2023/050569)
6. Superconducting Quantum Computing Circuit Package (Leek, Spring, patent WO2020035672)
7. Component Mounting Assembly (Goodwin, Blackmore, Doherty, application GB2313865.4)
8. Vacuum Viewport Member (Goodwin, Blackmore, Doherty, Gates, Gow, application GB2407985.5)
9. Oven Assembly for Producing Spatially Propagating Neutral Atoms (Goodwin, Blackmore, Doherty, Hughes, patent WO2023233136)
10. Ion Trap Assembly (Goodwin, Blackmore, Doherty, application GB2313868.8)

Patent applications 7 and 10 in the above list are based on research funded by the Hub's Partnership Resource Fund.

Spinout Case Studies

Universal Quantum

Founded in 2018 by Professor Winfried Hensinger and Professor Sebastian Weidt to commercialise EPSRC-funded research, is spin-out Universal Quantum. Universal Quantum recently collaborated with Hensinger's IQT research group at the University of Sussex successfully demonstrating the transport of qubits from one quantum computing microchip module to another with unprecedented speed and precision. This allows chips to slot together like a jigsaw puzzle to make quantum computers that can host sufficiently many qubits for fault-tolerant quantum computing with millions of qubits, enabling many of the groundbreaking applications quantum computers are known for. The technology, known as UQConnect, is now being commercialized by Universal Quantum to build large scale trapped ion quantum computers capable of solving some of humanity's greatest challenges.

In 2022 Universal Quantum received an order of €67 million from the German Aerospace Centre to build two quantum computers, and work is continuing on this through to 2026/2027.

ORCA

Hub-funded research, published and patented through to 2018, was commercialised through Oxford University Innovation and led to the founding of ORCA Computing in 2019. It won the Institute of Physics Start-Up Award in 2020. Following pre-seed investment, the company raised $15m in venture capital in 2022, and was selected by the Ministry of Defence to explore defence applications for quantum technology. In 2024, ORCA acquired the Austin, Texas-based Integrated Photonics Division of GXC. The company now employs around fifty people, with offices in London, Toronto (Canada), Krakow (Poland), and Seattle (US).

"Without the well thought-through national programme and the NQIT-managed funding in particular, ORCA Computing and our unique approach to enable networked photonic quantum computers would not exist. The ability to conduct quantum computing reliably is key to enable progress in other technologies such as AI, which is increasingly a major consumer of energy with its undesirable environmental impacts.

It is thanks to the national programme drawing the key people and ideas together that the UK is now at a critical point where it really could lead the world and establish a significant homegrown industry."

Richard Murray, co-founder and CEO of ORCA

Quantum Motion

Spin-out Quantum Motion was founded in 2017 by EPSRC-supported Professor John Morton at University College London and Professor Simon Benjamin of Oxford University. The company is developing a technology platform that includes a scalable array of qubits based on the silicon technology already used in smartphones and computers. Engineers are developing quantum computer architectures that are compatible with standard silicon processing, unlocking the power of quantum computing with the simplicity of silicon.

By creating a scalable quantum computing technology, the company will be able to tackle currently intractable problems in fields as diverse as chemistry, medicine, and artificial intelligence. In 2023, Quantum Motion achieved equity funding of over £42 million from some of the world's leading quantum and technology investors, including the Sony Innovation Fund.

QuantrolOx

QuantrolOx, an Oxford University spinout, is the developer of Quantum EDGE software for qubit, and quantum processor tune up automation. They envision a world where the bring-up, characterization and testing of every qubit will be fully automated enabling quantum scientists to spend less time tuning qubits and more time on advancing quantum computing, thereby accelerating the path to practical quantum computers. Quantum EDGE integrates with major quantum hardware providers by building on open-architecture principles enabling organizations to select the best components for their quantum systems.

The company was formed from work carried out in the University of Oxford Department of Materials. In 2022, QuantrolOx raised €2.5m of upfront grant funding from the European Innovation Council, with an additional €8m reserved as funds to match venture capital investments from other sources.

Relationship with the NQCC

Launched in 2020, the National Quantum Computing Centre (NQCC) has developed in parallel with the QCS Hub and has an important role in supporting the commercialisation of quantum technologies. In February 2021, the Hub and the NQCC signed a Memorandum of Understanding, strengthening their shared vision, and recognizing the profound impacts quantum computing is expected to have in advancing knowledge and scientific discovery, and for realising economic and societal benefits.

Under the MOU, the NQCC and QCS Hub pledged to work together to advance the field of quantum computing for the benefit of the UK, and unlock the advantages for wider society.

"This signing of this MOU marks an important step in our shared goal of making the UK a quantum ready economy" explained Professor Dominic O'Brien, Director of the Quantum Computing and Simulation Hub. *"We are looking forward to working closely with the NQCC to accelerate the development of this disruptive technology."*

NQCC Director, Dr Michael Cuthbert said: *"I am delighted we have established a shared vision under this MOU with the QCS Hub. Quantum computing will be an important technology in the coming years. Ensuring the NQCC and QCS Hub can speak and act with shared purpose gives confidence to the community and sets a further example of collaboration across our National Quantum Technologies Programme. I am particularly pleased we will have shared focus on skills, training and mobility, workforce development is important for our own organisations and vital for the growth of our industry partners across the sector."*

The organizations have benefitted from shared research including provision of hardware, and helped build the future workforce by promoting the mobility of researchers, working on collaborative engagement projects such as joint work with the UK finance sector, supporting training schemes and sharing access to each other's facilities.

Since the formation of the NQCC, the Hub UE Team have worked closely with business development partners at the NQCC to ensure a "joined up" approach to our respective engagement activities. We ran several joint NQCC-Hub events exploring the use of quantum computing in the financial services sector with major banks and regulators, and together supported the Digital Regulators Communication Forum (DRCF), developing their views on quantum computing, including appropriate training. With the NQCC, UE also provided guidance to the Financial Conduct Authority on quantum computing, and they published their views jointly with the World Economic Forum, advising businesses and regulators to ensure a collaborative and globally harmonized approach to quantum technologies.

Working With Other NQTP Organisations

In addition to the establishment of the NQCC, the overall landscape for user engagement in quantum computing has evolved considerably over the lifetime of the Hub, and the UE Team play a role in ensuring communication across the programme, where appropriate signposting to other UK Quantum organisations such as NPL and the Digital Catapult.

Working with the Institute for Manufacturing

Since 2022, the QCS Hub has been working with the Institute for Manufacturing (IfM) at the University of Cambridge. The UE Team collaborated on the organisation and running of several "round table" discussion events with industry. This led to a joint publication with the IfM which examined the landscape for quantum technologies in the UK economy, and how quantum computing can best be translated into increased productivity and economic growth.

This paper made several recommendations, including the formation of a forum for Systems Integrators and Consultancies who have a particular interest in quantum technologies. In 2023, the UE Team and the IfM scoped this idea further, with additional sessions with major UK IT Systems Integrators, and began a regular forum in 2024. Some of the IfM's work with the QCS Hub was subsequently discussed in *How To Introduce Quantum Computers Without Slowing Economic Growth* (Velu, C. and Putra, F., Nature, Vol 619, 461-464).

User engagement, collaborations and partnerships

User Engagement (UE) has been a core part of the QCS Hub's activities since it began. The UE team has ensured that the Hub is engaged with industry, both start-ups and established large companies, and has supported the Hub's role with policy makers and other external organisations, enabling the Hub to take a leading role in developing the UK's Quantum Economy.

Regular Engagement

There are around 50 external organisations with whom the UE Team are in regular contact. In addition to the 27 formal industrial partners in QCS Hub (23 in the predecessor Hub, NQIT) the UE Team regularly engages with new quantum start-ups, quantum platform providers, and national laboratories such as NQCC and NPL. We also have regular dialogue with Systems Integrators and IT Consultancies, and in particular have helped Tata Consultancy Services run a Quantum Challenge with their customers.

Over the last five years, the UE Team has presented at or attended many conferences, speaking with an estimated one hundred people per year.

QCS Hub User Engagement team member Keith Norman at a Careers in Quantum event.

Training and outreach

The UE Team has participated in several quantum computing public outreach events over the last five years, including presentations for the British Computing Society, Rotary Group Meetings, and other public events. In 2023 and 2024, the UE Team hosted work experience students as part of its public engagement activities, and we have supported Hub students to gain internship places in industrial settings.

In 2024, we organised a training course to provide our researchers with a greater understanding of bringing ideas out of the lab and into a commercial environment. This course took twenty Hub participants through the journey of idea creation through to spinning out and seeking funding. Two Hub researchers subsequently won £15,000 of prize funding and 12 months of free incubation support.

Externally, we have delivered tailored training to the Intellectual Property Office on quantum mechanics and the various quantum computing hardware modalities. We have also partnered with the NQCC on multiple occasions to present quantum computing to financial services sector audiences, and have reached several hundred people through this.

QCS Hub UE-organised commercialisation training

Contributions to External Reports

The team contributed to dialogues supporting external organisations' reports into quantum technologies, such as the Regulatory Horizon Council's 2024 report on a pro-innovation framework for quantum technologies, and the UK Parliament's 2023 inquiry into commercialising quantum technologies. UE also regularly supports and sponsors events for other research-led quantum organisations, such as the University of Edinburgh Quantum Software Lab and the Bristol Quantum Engineering Doctoral Training Centre.

The International Picture

The UE team has played a role in developing international relations around quantum computing. We have hosted several international delegations (including Poland, Japan, and Canada), and have liaised with other national programmes. In 2022 and 2023, we assisted the UK government with organising industry visits to US conferences, including the Quantum.Tech Silicon Valley and Boston Conferences, where we helped to arrange pitching sessions and meetings for the UK quantum startup community with potential US investors. The UE team also represented the UK academic community with US-based academia, quantum startups and established quantum organisations at knowledge-exchange events associated with these conferences.

The UE team has also published reports on the International State of Quantum Computing, and meets regularly with non-UK quantum computing organisations who may invest into the UK.

International State of Quantum Information Technologies Research reports

Partnership Resource Fund

Both NQIT and the QCS Hub have had a Partnership Resource Fund (PRF) for supporting additional research. Over ten years, this fund has allocated over £6m, enabling projects outside the scope of the original Hub work packages, and bringing new academic and industrial partners from across the quantum landscape into the Hub's networks. A particular benefit has been to allow funding of smaller projects to early career researchers, in some cases providing their first research award.

NQIT saw 44 collaborative projects with 35 companies and five non-Hub universities and awarded a total of £3.5m towards the costs of these projects. This was matched by circa £2.8m from industrial partners and £2m from other funders. Examples of spin-outs associated with NQIT included Oxford Quantum Circuits, Quantum Motion and Universal Quantum.

The QCS Hub has provided £2.7m of funding for 27 PRF projects, ranging from developing quantum algorithms to solve logistics problems, through to using quantum computing to create music. The latter led to the first International Symposium on Quantum Computing and Musical Creativity, and an online repository of tools and materials on creating music using quantum computing.

The 27 projects have brought four non-Hub universities into the QCS Hub partner network, the University of Exeter, the University of Plymouth, Heriot-Watt University and Nottingham Trent University. Alongside this, 16 industrial partners have brought more than £1m of external in-kind and monetary support.

Case Study

Dr Sarah Croke, University of Glasgow, PRF Project Lead, Quantum machine learning for gravitational wave data analysis:

"The format of the PRF mechanism allowed us to be much more agile in starting up a new project, and to sustain collaborative activity in a new area, which would have taken a lot longer to set up through traditional EPSRC mechanisms. Throughout the lifetime of the PRF we have recruited two PhD students to continue the work, each of whom won a prestigious scholarship, have secured UKRI funding for exchange visits for a new collaboration with US colleagues, and have recently been awarded a further EPSRC standard grant.

It's really been instrumental in sustaining and growing this activity, which also adds to the quantum algorithms effort in the UK as a whole. So, thanks very much, I think that the scheme is really very valuable in giving some flexibility to quantum computing funding support within the UK landscape.

Our original proposal identified capacity building, in particular career development of the named RA, Dr Fergus Hayes, an early career researcher, as an added value of the project. At the time of application Dr Hayes primary expertise was in gravitational wave astronomy, and he had been working with the PI and Co-I on a first project applying quantum algorithms to the field. The support of the PRF project enabled Dr Hayes to increase his expertise and profile in quantum computing, and he has since secured a position in quantum computing in industry, which also represents a successful outcome of the project. The project also gave opportunities to undergraduate and MSc students, as outlined above, to gain experience in the field. One of these has since been recruited as a PhD student, and was awarded a scholarship, to continue the topics explored in the PRF project."

Case Study

Project:
Flip-Chip Integration for Quantum Circuits

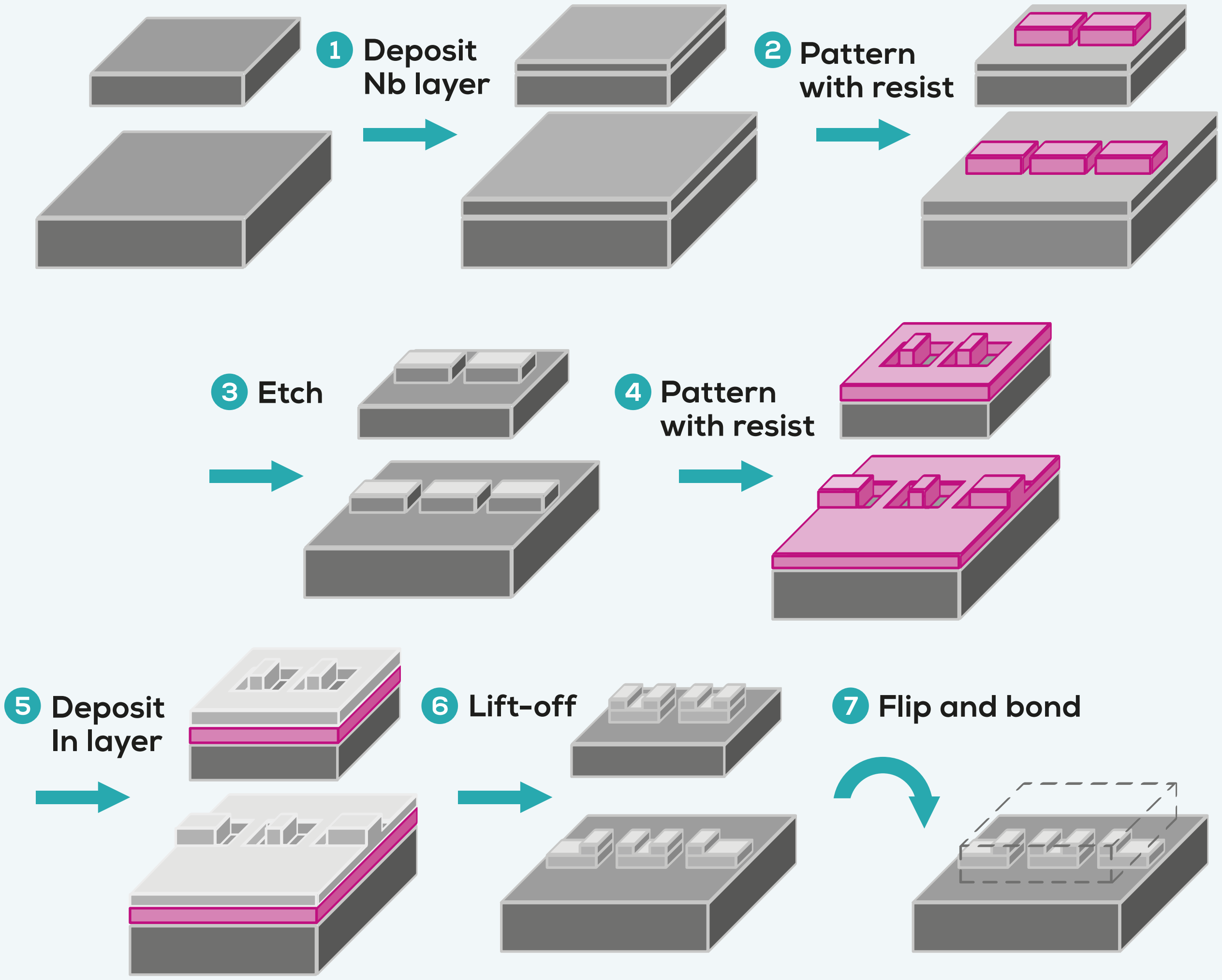
Project Lead:
Dr Malcolm Connolly

Institutions:
Imperial College London, University of Glasgow

Superconducting microwave circuits play a pivotal role in various quantum technologies, serving either as the primary quantum element or as ancillary circuitry for crucial functions like readout and control. The design of planar superconducting circuits, however, faces constraints due to limitations in on-chip connectivity and substrate material compatibility. This limitation has given rise to the emerging technology of flip-chip bump-bonding, offering a solution for vertically integrating circuits fabricated on separate substrates.

The implementation of bump-bonds not only addresses the constraints posed by planar geometry but also presents a pathway for the direct scaling of quantum devices. The benefits include shorter signal paths, higher packaging density, reduced parasitic connections, and enhanced mechanical stability. Enabling this technology in the UK was a key focus of this project, marked by the successful fabrication of a flipped superconducting resonator.

The ability to place the indium bumps with accuracy, to successfully align and bond the finished chip was demonstrated. This was a crucial step towards a reliable yield of this architecture and an important milestone. A detailed workflow for the bump-bonding process was developed by the James Watt Nanofabrication Centre, University of Glasgow.



The process-flow of fabrication

This study has direct applications to improved scaling of many quantum systems and the implementation of hybrid device architecture. This is a strategically important process for the UK with broad academic and industrial applications.

Responsible Research & Innovation

Responsible Research and Innovation (RRI) means undertaking research in a way that anticipates how it might affect people and the environment in the future so that we can gain the most benefit and avoid harm. Quantum Computing is a potentially transformative technology that is likely to have profound impacts on society, and a responsible approach to research and innovation is key if the benefits are to be maximised and any social challenges are to be anticipated and addressed.

A plan for RRI was embedded into the UK's Quantum Technologies programme from its inception, creating an example that has since been followed in numerous countries. The work in NQIT was led by Professor Marina Jirotka, and early in the programme an RRI Landscape Report was published. This report made recommendations on how to handle challenges in quantum computing and detailed a framework for a tailored RRI process. A briefing document on RRI in Quantum Technologies applied to Defence and National Security was published, also including issues for consideration by policy-makers.

The NQIT Hub was closely involved in the EPSRC-led public dialogue in quantum technologies, which sought to gauge the public's reaction to the potential impact of new systems, devices and products involving quantum principles. This included a series of workshops with a cross-section of the public, and led to a report that was the first of its kind at a global level. The findings also contributed to a short animated film to help open discussions with the public around quantum computing. Raising awareness of RRI across the quantum research community was considered to be a key element of the NQIT programme, and training workshops were held at the regular Hub Skills Forum.

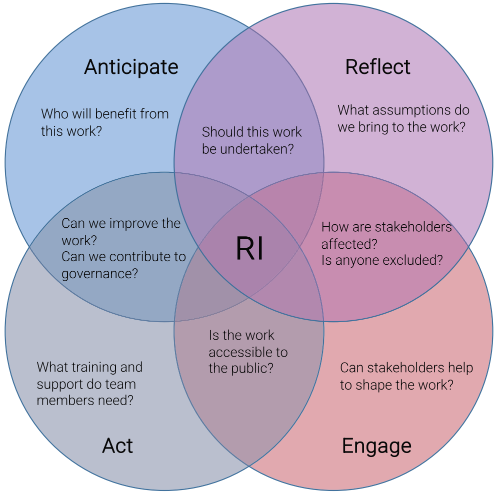


Image credit: Carolyn Ten Holter

After the transition from NQIT to QCS in 2019, the Hub supported a dedicated doctoral studentship focused on responsible innovation in quantum computing.

The QCS Hub funded a collaborative Industry Partnership project between Professor Jirotka's team and EY, considering Responsible Quantum Computing Communications. The project had three core objectives: to address perceived gaps in cross-departmental communication within policymaking teams and departments; to facilitate and support ongoing public dialogue and awareness; and to deploy responsible-innovation-based translational frameworks for QC spinouts into industrial/commercial contexts. Impacts from the project included: the delivery of the first ever societal-impact-focused workshop at IEEE Quantum Week Seattle (in partnership with NQCC and IBM); community engagement with members of the public; discussions with the novel technology office at NATO (Brussels); input into ongoing World Economic Forum work on quantum governance; an expert survey; a joint White Paper with EY; an animated short film about the inclusive and responsible development of quantum computing; and a research exchange with the Quantum Netherlands team at Delft TU.

The PRF project also led indirectly to a Policy Fellowship for Dr Carolyn Ten Holter to undertake a secondment at the Department for Science, Innovation and Technology, supporting work on the governance of quantum computing.

In 2023 it was recognised that several years had passed since the EPSRC public dialogue in quantum technologies and that an updated exercise could provide new insights. In the context of a developing commercial quantum computing sector, and a general shift in public conversations and awareness around novel technologies, the QCS Hub and Professor Jirotka's team undertook a new public dialogue activity in 2024. The purpose of this was to understand public perceptions of quantum computing and engage the public in an informed discussion about the development of quantum computing, particularly against an increasing background of news stories about the negative effects on society of technologies such as artificial intelligence, social media, and smartphones. The work began with a nationally representative survey to measure broad public attitudes to quantum computing, governance, and novel technologies, followed by a series of workshops to delve more deeply into opinions and to attempt to discover any concerns.

The QC Hubs have ensured that the UK has been at the forefront of RRI efforts in quantum computing. With the National Strategy's ambition to create a national and international regulatory framework supporting innovation and the ethical use of quantum technologies, building on this as we move forward will be critical.

Building the future

The UK National Quantum Technologies Programme aims to create a coherent government, industry and academic quantum technology community that gives the UK a world-leading position in the emerging multi-billion-pound new quantum technology markets. In implementing this, a key part of the activities of the Technology Hubs in both phases of the UKNQTP has been to establish and support the development of future researchers and leaders in Quantum Technologies and provide a consistent and clear voice to the UK.

The QCS Hub has provided opportunities to early career researchers to develop their skills, build their careers and consider commercial engagement through spin-outs. We have provided several targeted events, including training in entrepreneurship. In 2024 a group of students and early career researchers met for a researcher retreat, undertaking a comprehensive programme of activities, networking, and skills development. The Hub has provided support to Fellowship applications and has added two ECRs to the Hub investigators. The 10 years of quantum computing Hubs have also facilitated the funding of nearly 80 PhD students supervised by Hub investigators.

The quantum computing landscape has changed over the decade of the two Hubs and we expect that to continue. The announcement of the next phase of the Quantum Technologies Hubs to start at the end of 2024, the continued development of the NQCC, the establishment of the Office for Quantum in UK Government, and the development of quantum missions show the evolution and maturing of the technology, and the context in which it is seen. The UK is well-placed to capitalize on the future opportunities that quantum technologies offer, and the Hubs are pleased to have played a significant role in the development of the knowledge, innovation and skilled researchers that underpins this.

Outreach and engagement

The development of an engaged, skilled, and growing community of academics, researchers, technicians, and entrepreneurs is critical to enable the growth of the UK quantum computing community, and to establish a self-sustaining ecosystem around the needs of both academic research and commercial developments. This requires young people to choose STEM subjects and follow them into higher education and beyond. The QCS Hub has engaged at multiple levels to encourage young people to choose STEM options in school and further education, and then to continue into quantum technologies.

In collaboration with the other technology hubs we have supported the Quantum City activities and website, and in 2023 we also worked together on an International Summer School in Quantum Technologies for UK and Canadian students.

Quantum City

An important outreach resource has been Quantum City. This initiative, and its associated website, aims to provide information to explain how quantum physics has already contributed to existing technologies, such as lasers and semiconductors, and how developments with quantum science, funded from the NQTP, will make a positive difference to everyday life.

Aimed at both school children and adults interested in understanding more about quantum technologies, the Quantum City website, with the support of science events and the availability of resources for schools, has provided information on the impacts of quantum technologies in applications from medicines, finance, and energy use, to telecommunications, imaging and computing. The Quantum City initiative has been coordinated by the four QT Hubs.

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Outputs (PRF Projects)

Project	PRF Category	Lead Investigator	Lead Institution
SQUARE : Scalable QUbit AddREssing	Academic	Booth	Oxford
Emulator of noisy near-term superconducting architectures	Academic	Sanchez	Edinburgh
CaQTUS - (Calcium Quick Turnaround Universal System)	Industry	Lucas	Oxford
Cryogenic qubit control interface using analog/mixed-signal circuits and systems	Academic	Heidari	Glasgow
Quantum Computing for Modern Cryptography (QCMC)	Academic	Wallden	Edinburgh
Transform-limited GHz-bandwidth control lasers for photonic simulators	Industry	Kolthammer	Imperial
RFSQ: Radio Frequency engineering for large scale Spin control in solid state Quantum systems	Academic	Balram	Bristol
Quantum Computing and Music	Industry	Miranda	Plymouth
Quantum mechanical simulation of the fabrication process of aluminium oxide tunnel junctions as superconducting qubits	Industry	Georgiev	Glasgow
Silicon qubit control with a 3D microwave cavity	Industry	Fogarty / Fisher	UCL
Quantum compatible flip chip	Academic	Connelly	Imperial
MICRODOT: Microlens Integration for Compact & Robust Optical Delivery on Trap	Academic	Goodwin	Oxford
Spin Qubits in Hexagonal Boron Nitride	Industry	Luxmoore	Exeter
Atomic quantum frequency conversion of on-demand photons	Industry	Clark	Bristol
Quantum Amplification with Non-Linear Capacitance (QuANCap)	Academic	Warburton	UCL
Demonstrating analogue quantum computing approaches to optimisation using arrays of individually trapped neutral atoms	Academic	Pritchard	Strathclyde
Quantum machine learning for gravitational wave data analysis	Academic	Croke	Glasgow
Distributing big quantum computations over small quantum computers	Academic	Heunen	Edinburgh
Robust quantum computation on superconducting qubits with fixed coupling	Industry	Le Ginnosar	Surrey
Quantum Optimization for Logistics and Services (QOLS)	Industry	Corne	Heriot-Watt
Coherent diamond microcavity system with group-IV colour centres	Industry	Gangloff	Oxford
Dielectric meta-surfaces for low-loss quantum photonic interconnects	Academic	Patel	Imperial
Ion Trap Cavity Opto-Mechanics	Industry	Goodwin	Oxford
ResQCCom (Responsible Quantum Computing Communication)	Industry	Jirotka	Oxford
Quantum non-unitary time evolution to simulate normalised non-unitary dynamics on quantum computers	Academic	Wilmott	Nottingham Trent
Memory-optimal classical simulation of quantum data	Academic	Shahandeh	Royal Holloway
Scalable Gatemon Quantum Computing with FPGA Cryo-electronics (CITROEN)	Industry	Delfanazari	Glasgow

Downloadable Reports

A number of reports are available to download from the QCS Hub website. These are an ideal startinig point for those looking to navigate their way around the quantum computing landscape.

A Quantum Simulation report provides an accessible overview of quantum simulators, their technology and their likely applications. Quantum simulation is an often overlooked part of the Quantum Information Technology (QIT) revolution that is currently happening around the world.

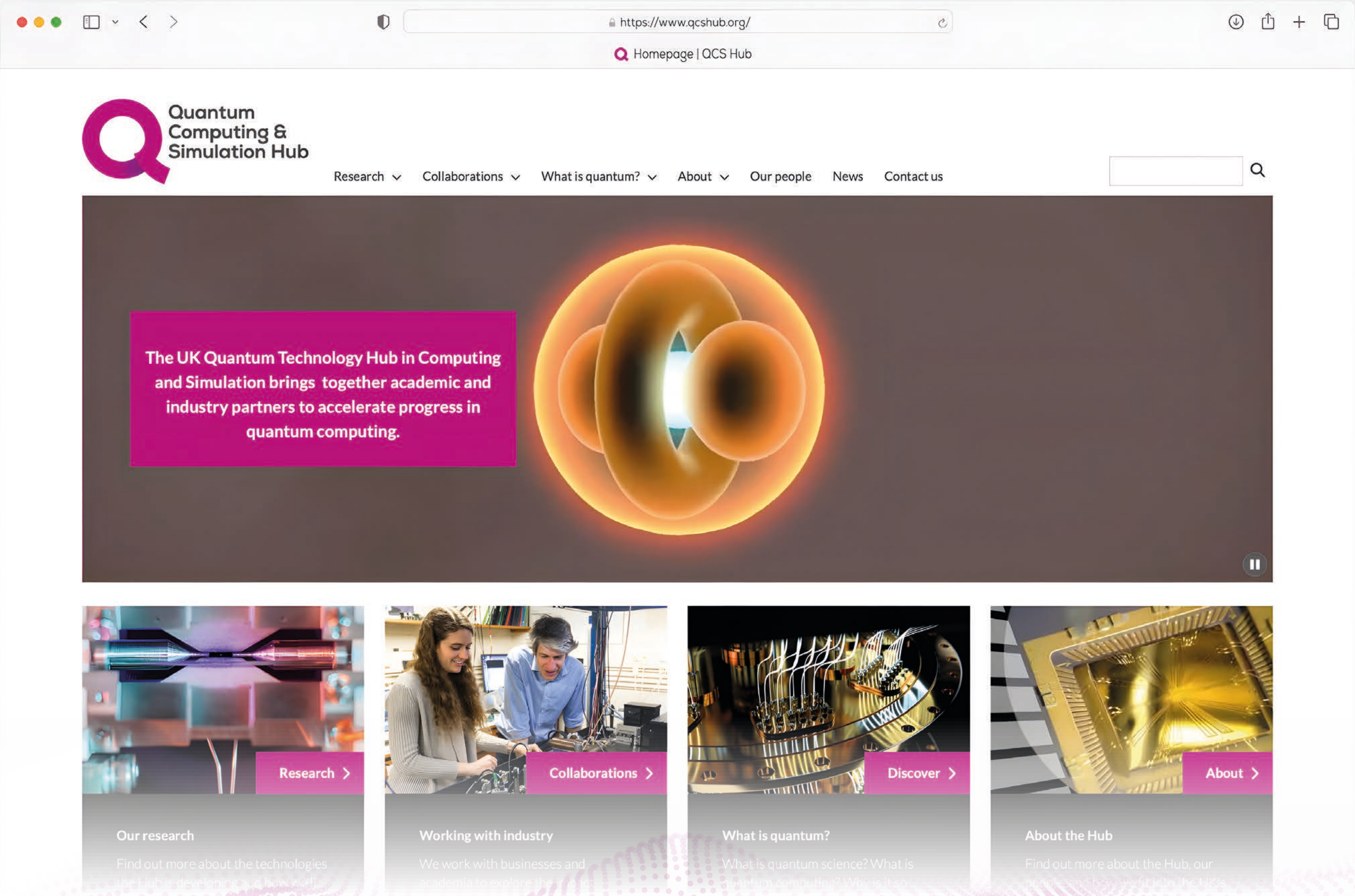
We also have a two-part report that summarises global activity in quantum technology. The first part presents a snapshot of activities across Europe, focusing on governmental and large-scale groupings and activities, showing their scale and the growing involvement and maturity of the industrial sector. The second looks at the rest of the world, highlighting activities across North America, Asia, Russia and Australia.

To find these and others, visit
https://www.qcshub.org/resources

Hub members at our January 2023 Project Forum event

Further information

You can find out more about the Hub on our website at **www.qcshub.org**



https://www.qcshub.org/

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Quantum Computing & Simulation Hub

The UK Quantum Technology Hub in Computing and Simulation brings together academic and industry partners to accelerate progress in quantum computing.

Our research

Find out more about the technologies the Hub is developing and how we'll

Working with industry

We work with businesses and academia to explore the

What is quantum?

What is quantum science? What is quantum computing? Why is it so

About the Hub

Find out more about the Hub, our people and how we fit into the UK's

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