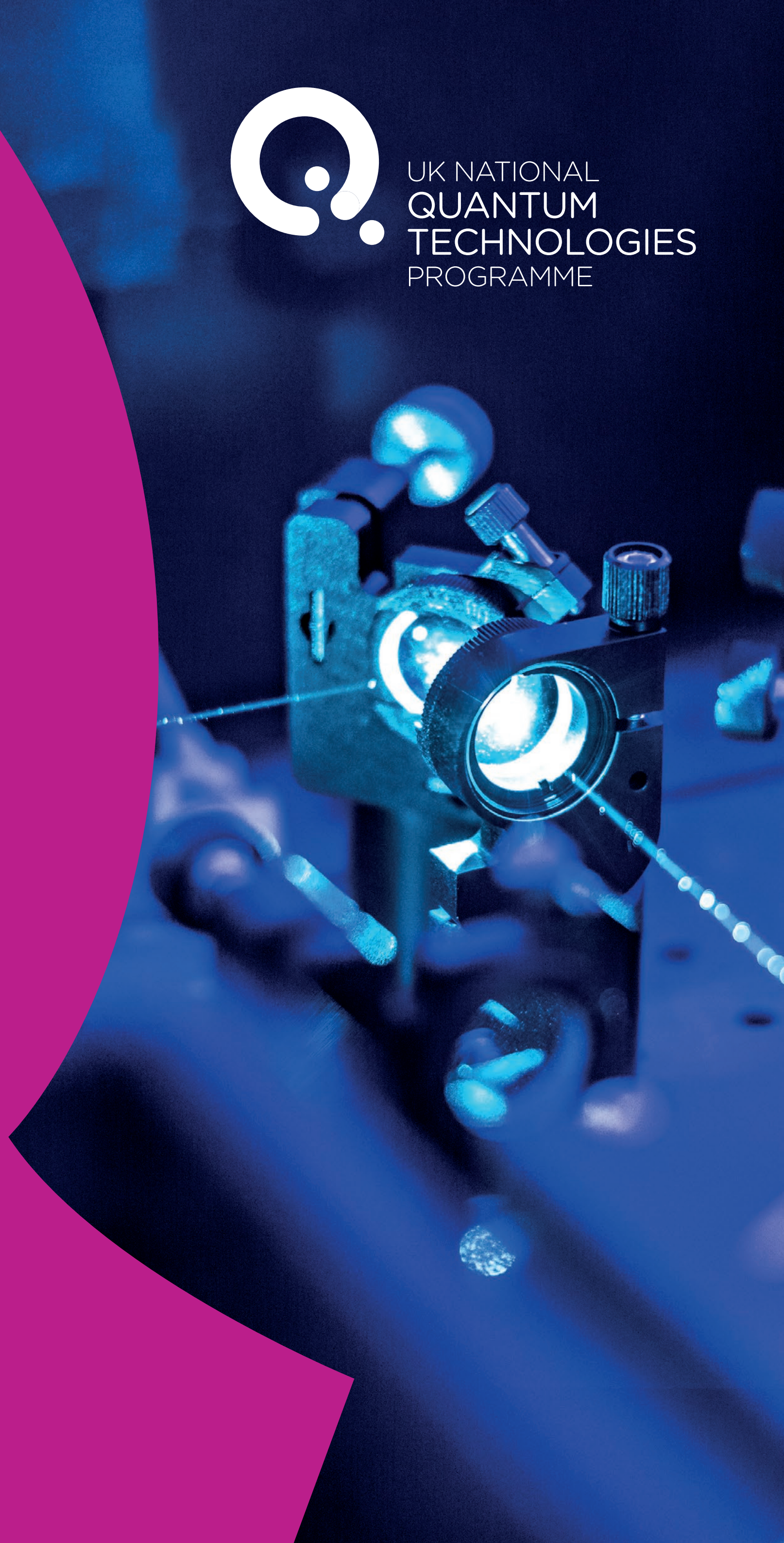
Quantum Computing & Simulation Hub

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Progress Report

2019-2022



Dr Raghu Srinivas from the ion trap quantum computing research group at the University of Oxford | John Cairns Photography

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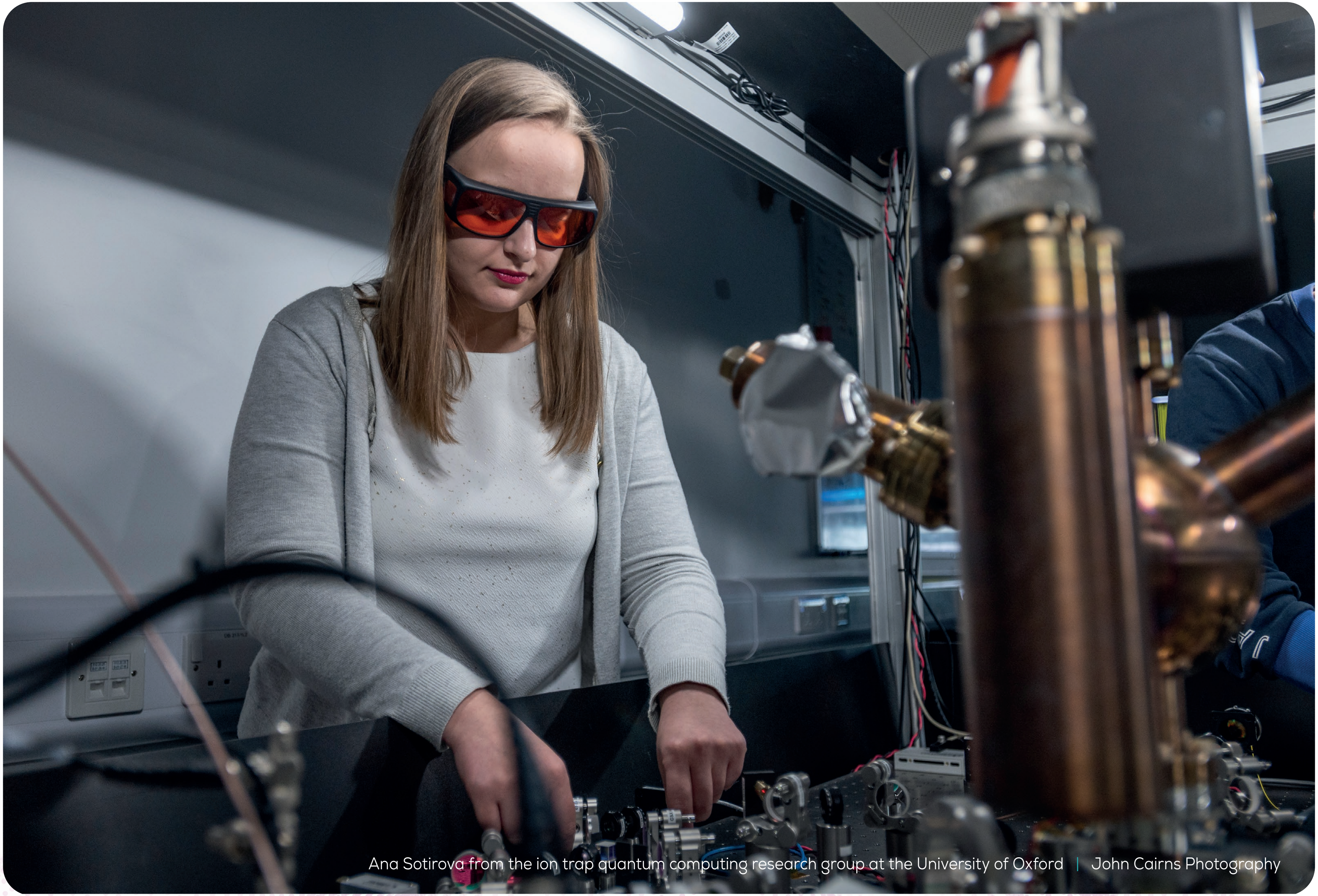


Ana Sotirova from the ion trap quantum computing research group at the University of Oxford | John Cairns Photography

Introduction

The Hub in Quantum Computing and Simulation has had a successful three years, and we are pleased to be able to present a snapshot of our achievements so far. We started a few months before the first pandemic lockdown in 2020, and only had our first Hub-wide in-person meeting in May this year. Our achievements are a tribute to the hard work and dedication of our investigators, researchers, students, administration team, and my fellow Directors. I would like to thank everyone for their efforts in what were very difficult circumstances.

Quantum Computing is rapidly evolving worldwide. The range of platforms available and their capabilities continues to increase, with ambitious roadmaps toward quantum advantage. There are many substantial government programmes, and a growing number of startups. Another sign of an increasingly mature landscape are recent startups focusing on the subsystems and systems that will be required around the qubits themselves. In the UK the National Quantum Computing Centre is growing rapidly, with a building under construction and a rapidly growing set of activities. We meet the NQCC regularly, and are beginning to collaborate on individual research projects. NPL also has a growing activity in quantum standards, and the Hub is supporting this activity, in addition to the existing individual collaborations we have.

Alongside the other UK quantum hubs, we continue to be an important part of the growing UK ecosystem, providing new ideas, training PhD students addressing critical research challenges, and helping to connect partners across industry, academia, and government. At the core of our mission is to deliver rigorous leading quantum technology oriented research, and by February this year we had published ~70 publications with around 1400 citations. This shows the relevance of the work we do to the wider community.

Hub engagement activities continue to evolve. Notable is our long-term engagement with the Financial Conduct Authority (FCA), in partnership with the NQCC. This has grown into engagement with a number of government departments as well as the banking sector and the regulator. Here, access to the leading academics and the neutral advice that the Hub can provide is valued by our partners, and the information we gather helps the UK understand how QC will impact this area. Despite the pandemic, startups continue to be formed from work from or supported by the Hubs, with two launched and several more in the process of formation.

Our partnership resource funding has been extremely valuable in bringing in new ideas, investigators, and industry. We have funded 24 projects, and as you can see from the report some projects are now complete, with some substantial successes. We also continue to work with the other hubs on engagement with the public, through Quantum City, and are also funding work on responsible research and innovation, in order to ensure the community is part of the evolving quantum technology landscape.

I hope you find this report useful. Please get in contact with any of the team if you would like to know more.

Dominic

Professor Dominic O'Brien
QCS Hub Director

Hub Overview

Introduction

The Quantum Computing & Simulation Hub (QCS) is a collaboration between 17 UK universities and is one of the four hubs within the UK National Quantum Technologies Programme. Working with an extensive network of academic, industrial, and governmental partners, we are focused 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 citizens to ensure the UK is 'quantum ready'. Our aim is to accelerate progress within quantum computing and ensure the UK becomes, and remains, a leader in the emerging global quantum information economy.

Heritage

The QCS Hub 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-node connectivity with a world-leading combination of rate and fidelity; it 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 late 2019 with a renewed ambition to create a quantum information economy in the UK.

Research

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

Our programme is divided into a number of 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

These areas of investigation are 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.

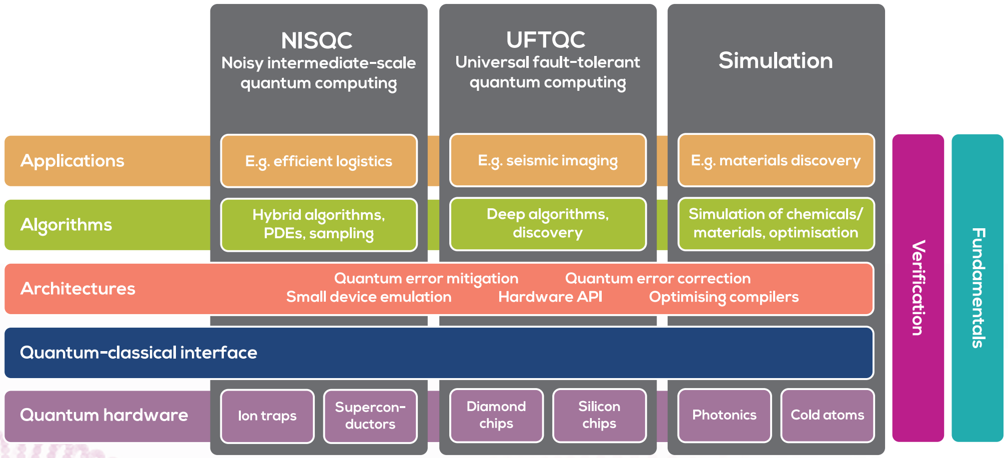


Figure 1: Key themes and research areas within the Hub

Noisy Intermediate-Scale Quantum Computing (NISQC) offers the opportunity to deliver applications in areas such as optimisation tasks and emerging ideas such as quantum-enhanced machine learning. One of the Hub's key aims in this area is to implement 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 is 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.

The **Simulation** theme focuses 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.

Studentships

The Hub receives an annual allocation of EPSRC-funded doctoral training programme studentships which are allocated through a competitive call open to the 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. We typically have between 30 and 40 Hub students supported within the Huband every effort is made to offer opportunities to these students to contribute to Hub events and to present their work. These students make a strong contribution to the quantum community and frequently move on to research positions within the Hub or spin-out companies.

Responsible research and innovation

Responsible Research and Innovation (RRI) and Trusted Research are important considerations for the Hub, and we have been supporting RRI work through student support, a PRF project, and briefings and training from RRI experts. As a joint initiative with the other quantum technology hubs, working with a team from the Centre for the Protection of National Infrastructure, a seminar on trusted research was provided for the hub researchers in May 2022.

Career development

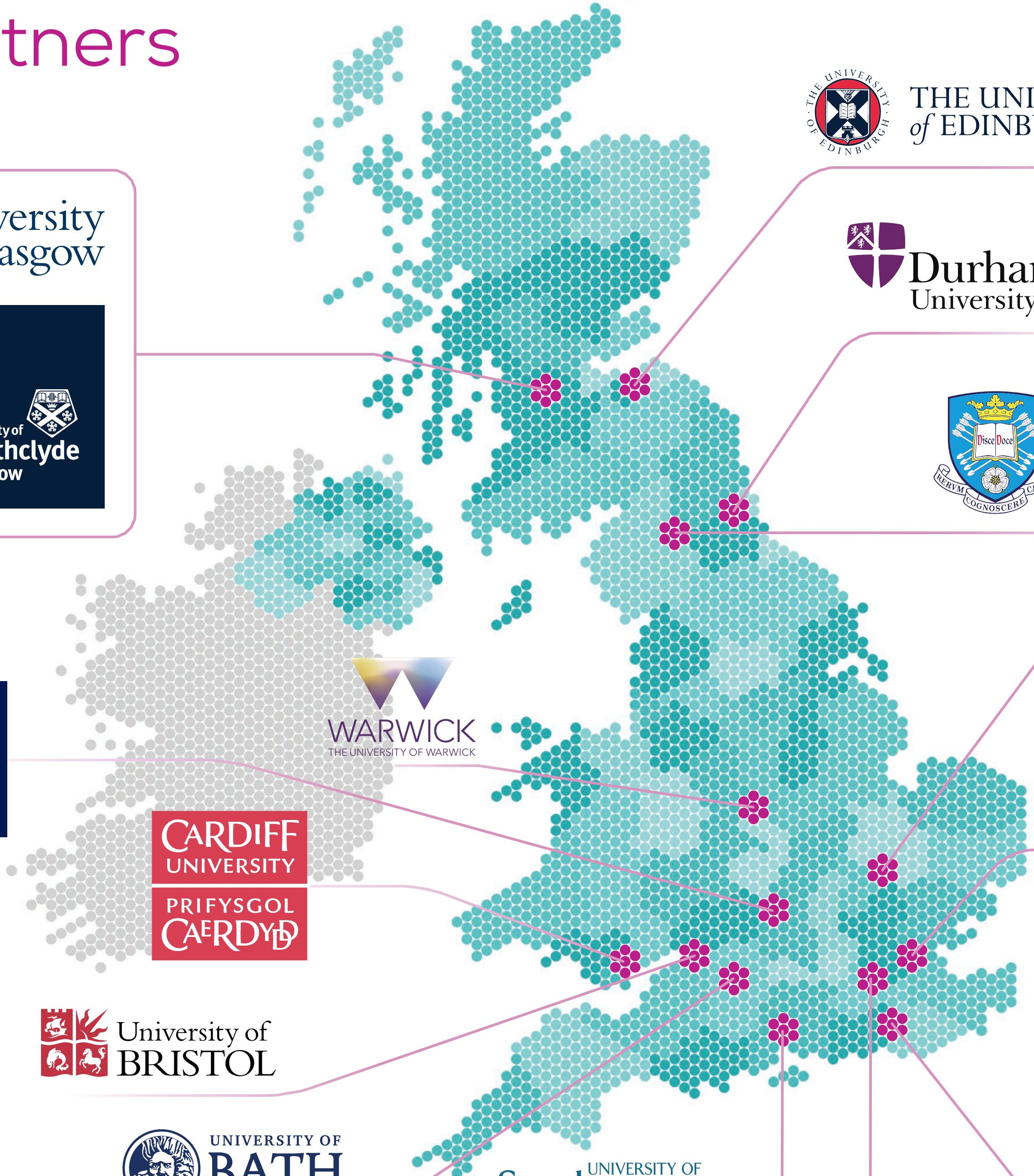
The Hub has endeavoured to support its early career researchers (ECRs) with a number of initiatives, including a researcher committee that has met regularly with the Hub Director. Alongside other training activities, we have run a "Researcher Day" event that included a diverse range of speakers from academic and industrial partners, talking about how their careers had progressed and how our researchers might consider developing their 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 followed this approach. We have also supported a number of Fellowship applications through individual mentoring and letters of support, and have also added ECRs to the Hub academic team.

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.

We also have a User Engagement (UE) team - Technology Associates Christopher Noble and Keith Norman, led by Evert Geurtsen - who are 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



THE UNIVERSITY of EDINBURGH

Durham University

The University Of Sheffield.

UNIVERSITY OF CAMBRIDGE

Imperial College London

UCL

ROYAL HOLLOWAY UNIVERSITY OF LONDON

UNIVERSITY OF SUSSEX

UNIVERSITY OF SURREY

UNIVERSITY OF Southampton

UNIVERSITY OF BATH

University of BRISTOL

CARDIFF UNIVERSITY PRIFYSGOL CAERDYD

UNIVERSITY OF OXFORD

WARWICK THE UNIVERSITY OF WARWICK

University of Glasgow

University of Strathclyde Glasgow

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), which preceded QCS.

Evert Geurtsen
Co-Director for User Engagement

Evert Geurtsen is an engineer with a background in the international automotive industry and new product development, having undertaken senior leadership roles at well-known brands including General Motors and Group Lotus. He has also founded his own ventures and raised investment pioneering the introduction of affordable electric cars. More recently, he led the IP commercialisation and new venture creation for the physical sciences at Oxford University Innovation (OUI), where he and his team helped founders to start and raise investment for more than 50 new ventures, and he created Oxford's Startup Incubator. In 2017 he became Co-Director for User Engagement in the NQIT Hub, which preceded QCS. Evert will be retiring from the Hub at the end of November 2022.

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. They are also involved in theoretical activity, concerned mainly with quantum fault-tolerant methods and quantum error correction.

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, the Optical Society (OSA), the American Physical Society, and the Institute of Physics. He was the Director of the Networked Quantum Information Technologies Hub (NQIT), which preceded QCS.

Professor Elham Kashefi

Elham Kashefi is Professor of Quantum Computing at the School of Informatics, University of Edinburgh, and Directeur de recherche au CNRS at LIP6 Sorbonne Université. She co-founded the fields of quantum cloud computing and quantum computing verification, and has pioneered a trans-disciplinary interaction of hybrid quantum-classical solutions from theoretical investigation all the way to actual experimental and industrial commercialisation (Co-Founder of VeriQloud Ltd). She is the founder of national quantum networks (QuOxIC and QUISCO) and member of multiple institutions (CQIQC in Canada, Li-Fi R&D Centre in Edinburgh, PCQC in France). She has been awarded several UK, EU and US grants and fellowships for her works in developing applications for quantum computing and communication. She served as the Associate Director of the NQIT Hub before being elected to lead the software activities within QCS.

Management board

The Management Board of the Hub, chaired by the 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 oversees ED&I, consider programme risks, agree budgets and changes to the work programme, and allocate funding for partnership resource and strategic collaborations.

Professor Dominic O'Brien

Evert Geurtsen

Professor David Lucas

Professor Ian Walmsley

Professor Elham Kashefi

Professor John Morton

Professor Simon Benjamin

Professor Noah Linden

Work-package leaders

Our work-package leaders are each responsible for leading our research in specific areas. David Lucas, the Hub's Principal Investigator, leads the Hub's work on Ion traps while Elham Kashefi, from our senior science team, leads our research into Verification, Validation and Benchmarking. Our research into other areas is led by:

Dr Peter Leek

Superconductors

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.

Professor Jason Smith

Superconductors

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).

Professor Anthony Laing

Photonics

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.

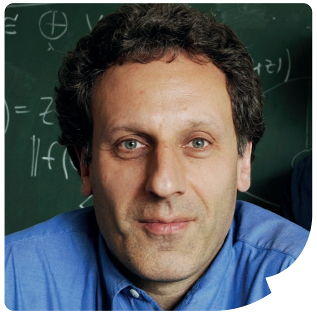
Professor John Morton

Silicon quantum processors

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.

Professor Andrew Daley
Cold Atoms

Andrew Daley is Professor of Theoretical Quantum Optics at the University of Strathclyde, in Glasgow. Prior to taking up this Chair, he held a faculty position at the University of Pittsburgh, after being a senior researcher at the Institute for Quantum Optics and Quantum Information of the Austrian Academy of Sciences in Innsbruck, Austria. As well as leading the Hub's work on cold atoms he is in the leadership team of the EU Quantum Technologies Flagship project on Programmable Atomic Large-Scale Quantum Simulation.



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.

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.

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 focusses on both the capabilities of near-term Noisy Intermediate-Scale Quantum (NISQ) Computers and large-scale fault tolerant quantum computers.

The National Quantum Technologies Programme

The UK National Quantum Technologies Programme (NQTP) is a co-ordinated partnership between industry, academia and government, with total investment now exceeding £1 billion. More than 140 companies - from high-tech start-ups to global corporations – are part of the programme, alongside government agencies and 38 British universities.   Its role is to accelerate advances in quantum technology research and their translation into practical applications.

The Hub plays a key role in the programme, as one of four quantum technology hubs focussed on different aspects of quantum technology, which have shared over £200 million of investment through EPSRC. The Quantum Technology Hub in Sensors and Timing is led by the University of Birmingham; QuantIC, which focuses on quantum-enhanced imaging, is led by the University of Glasgow; and the Quantum Communications Hub is led by the University of York.

The NQTP's mix of public and private investment is fast-tracking results with real-world impact across the economy and society. Government funders and delivery partners for the NQTP are:

- The Department for Business, Energy and Industrial Strategy (BEIS).

As part of UK Research and Innovation (UKRI):

- The Engineering and Physical Sciences Research Council (EPSRC).
- Innovate UK.
- The Science and Technology Facilities Council (STFC).
- Innovate UK KTN.

And:

- The Defence Science and Technology Laboratory (Dstl).
- Government Communications Headquarters (GCHQ).
- National Physical Laboratory (NPL).

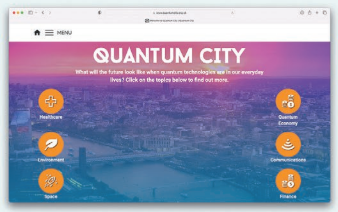
Within the NQTP, the Hub works in partnership with the **National Quantum Computing Centre**, based at the Rutherford Appleton Laboratory Campus (RAL) at Harwell in Oxfordshire. Our shared aim is to grow the UK quantum computing ecosystem, and to ensure the UK has the supply chain, user base and skills to exploit the transformative capabilities that quantum computing will bring for the benefit of the nation.

Featured Paper

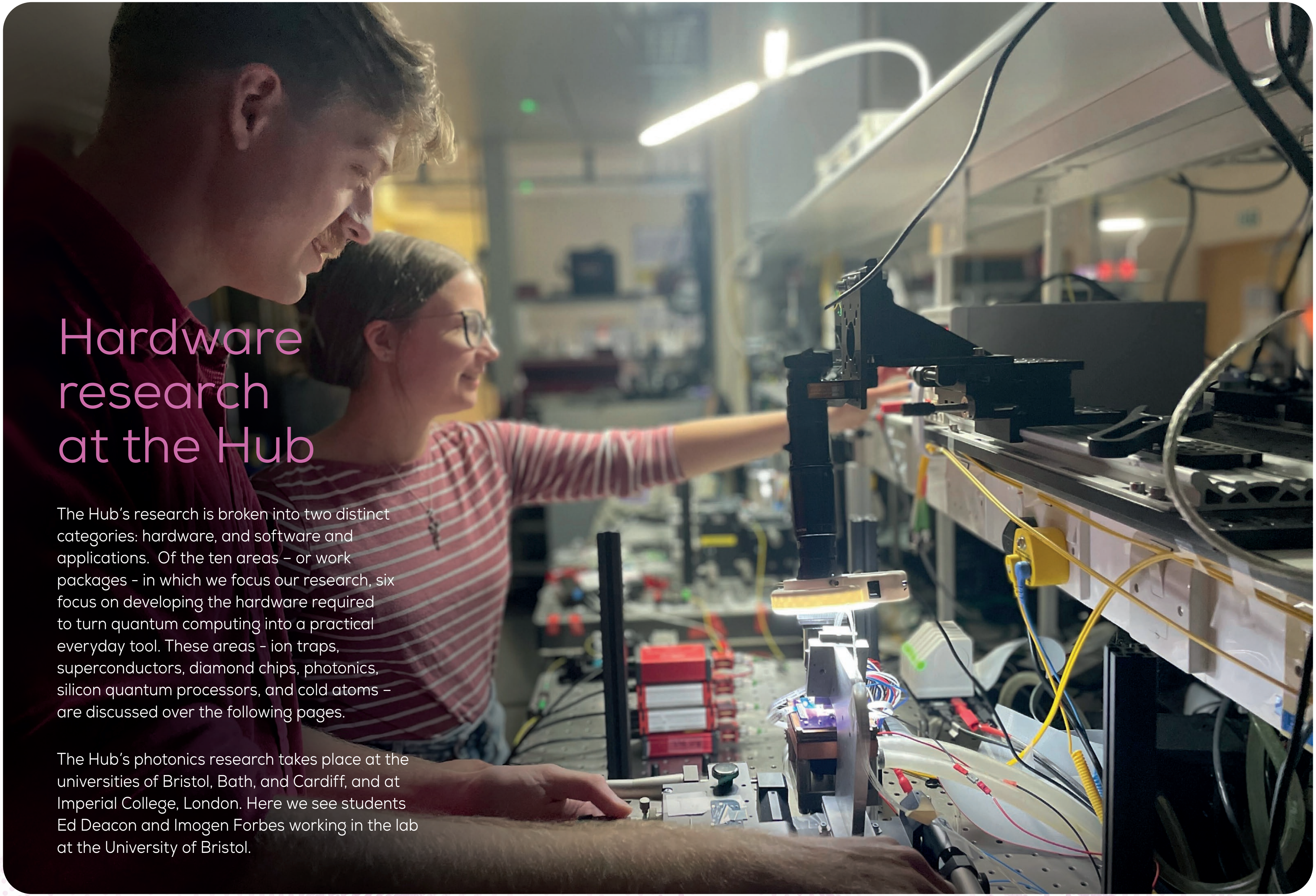
Public engagement: Quantum City

The Hub is an active participant in Quantum City, an NQTP public engagement programme led by the four quantum technology hubs, in association with NPL and UCLQ. It aims to raise the profile of quantum technologies amongst the public and schools, and facilitate discussions about the role of these technologies in society. It also works to encourage the uptake of STEM subjects and signpost career pathways in the fields of quantum science and technology development, to help build a future quantum workforce.

Quantum City's key engagement tool is its website, which sits alongside a programme of events, which in 2022 included New Scientist Live exhibitions in both London and Manchester. The website has a wide range of resources for schools and a downloadable *Everyday Guide to Quantum Science*. Almost a third of all UK schools have received Quantum City posters and a series of virtual 'Quantum Assemblies, in association with The STEM Hub, have enabled Quantum City to put researchers into hundreds of classrooms across the UK. These have reached 3000-5000 students per event and we are looking forward to presenting the first quantum computing assembly in December 2022.



The Hub is an integral part of the National Programme and perhaps the most striking evidence is in the close collaboration between the Innovate UK Quantum Commercialisation challenge and the Quantum Technology Hubs. Each Innovate UK call has involved the Hubs through consultation, joint cultivation events and broad networking efforts to bring together the right partners. The results are bids and projects of the highest standards involving industry partners, RTO's and universities that together form the core of the UK's evolving quantum eco-system.



Hardware research at the Hub

The Hub's research is broken into two distinct categories: hardware, and software and applications. Of the ten areas – or work packages - in which we focus our research, six focus on developing the hardware required to turn quantum computing into a practical everyday tool. These areas - 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

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. However, it is recognized 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; the Hub's research addresses both of these challenges.

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

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 [0]. We have proposed methods for making microwave-driven gates more robust to typical noise sources [1]. We have also investigated methods for diagnosing motional coherence (on which ion trap quantum logic operations usually depend) [2].

Chip trap development

A cryogenic system based around a microfabricated chip trap has been constructed for the purpose of increasing the speed of microwave-driven gates [3]; preliminary data show the gate speed is at least ten times faster than our previous results. We have constructed a dual chip-trap system as a demonstrator for beyond-single-chip scalability, and shuttled a qubit back and forth between the chips at high speed (<1ms), achieving millions of transfers without loss [4].

Quantum networking

A central theme of our 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 a promising method for distributed computing and modular scaling, the techniques have applications in quantum communications and metrology. The two-node network which we constructed in the Phase 1 NQIT Hub demonstrated a world-leading combination of fidelity and rate of remote entanglement generation, across all physical platforms [5]. We used this system to make the first full demonstration of a "device-independent" quantum key distribution protocol, where the security is derived from the use of entangled qubits with minimal assumptions about the behaviour of the physical apparatus [6]. 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) [7]. 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 100 seconds [8].

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 have demonstrated enhanced ion-cavity coupling using cavity cooling techniques [9]. We have also studied theoretically the use of non-spherical cavity mirrors and shown that this can enhance the atom/cavity coupling [10]. We are developing fabrication techniques to enable the precise integration of miniature optical cavities with microfabricated ion traps.

Ion trap partnership projects

The core activity of our ion trap work has been supplemented by several Partnership Resource Projects, for example: an industrial PRF "CaQTUS" (with Oxford Ionics Ltd) to develop a quick-turnaround system for testing chip traps, and an academic PRF "SQUARE" to develop a photonic waveguide chip for laser-addressing an array of ions in a single trap. The Quantum Communications Hub has also provided PRF funding to investigate increasing the range of the device-independent QKD demonstration to longer fibre links.

[0] A.C.Hughes *et al.*, Phys. Rev. Lett. 125 080504 (2020).
[1] C.H.Valahu *et al.*, New J.Phys. 23 113012 (2021).
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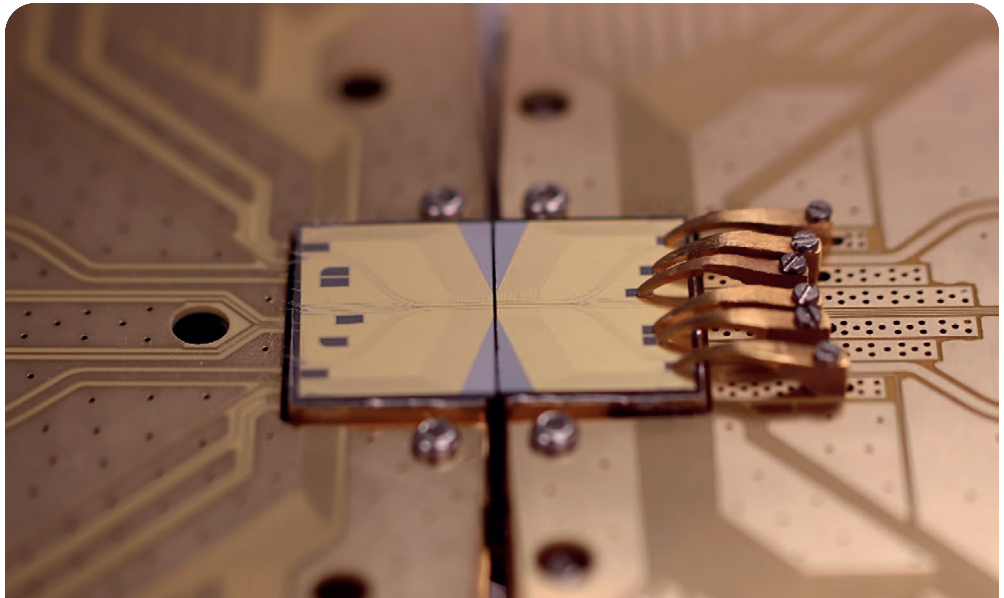
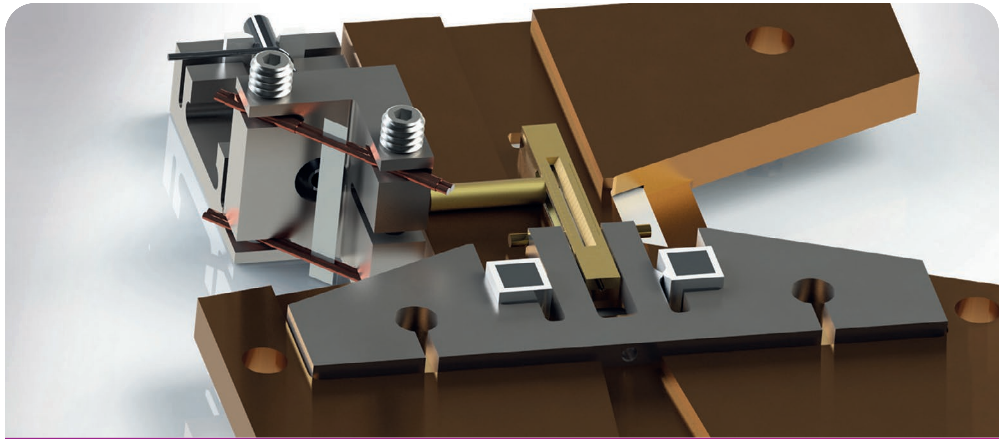
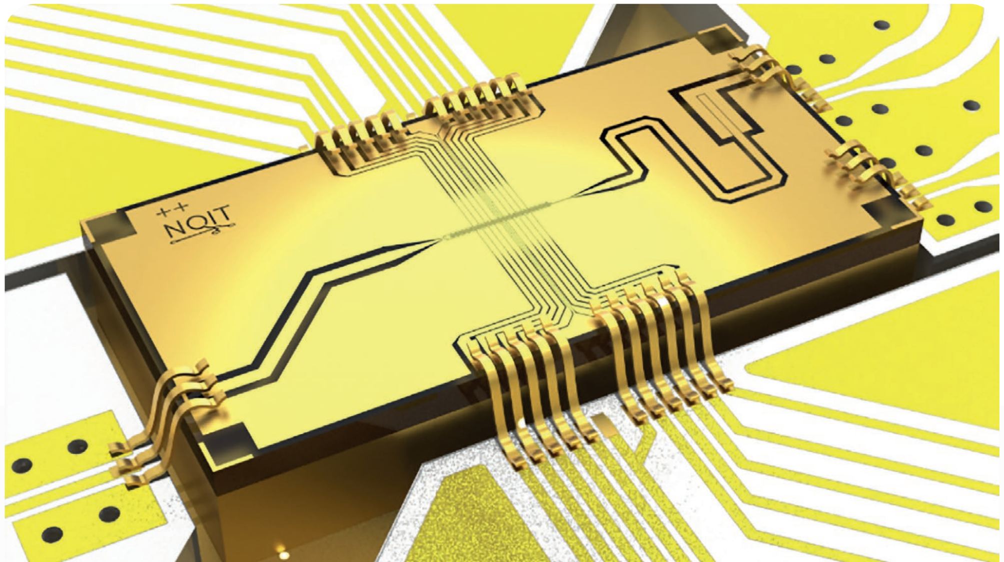


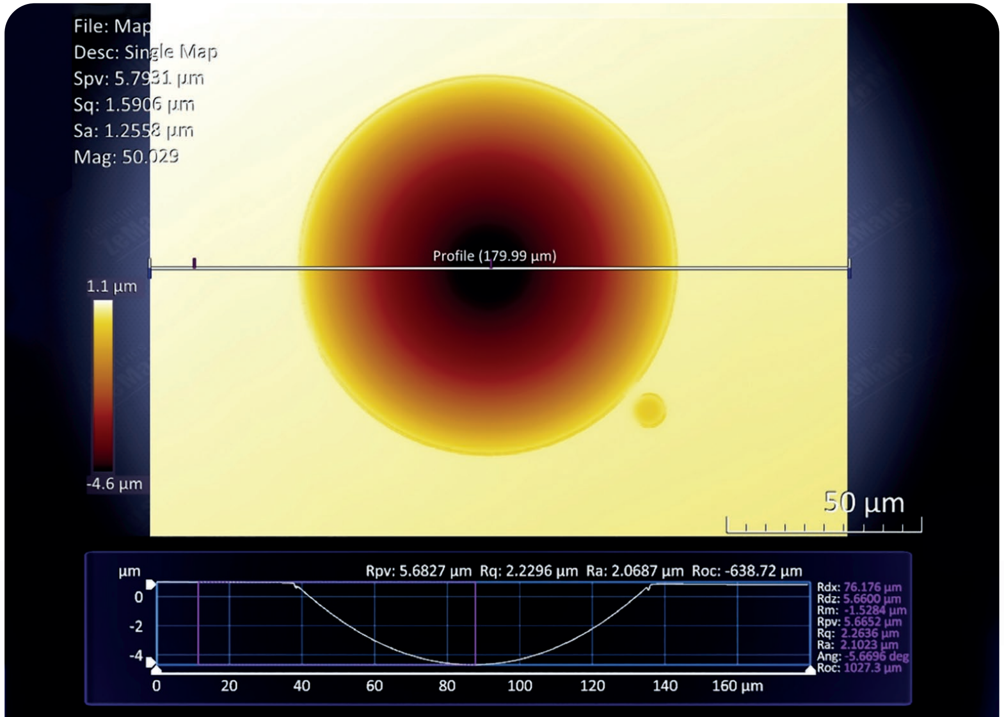
Twin ion chip trap setup at Sussex University. [Winni Hensinger]



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



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



Surface profiling of prototype cavity mirrors at the University of Southampton. [James Gates]

Featured Paper

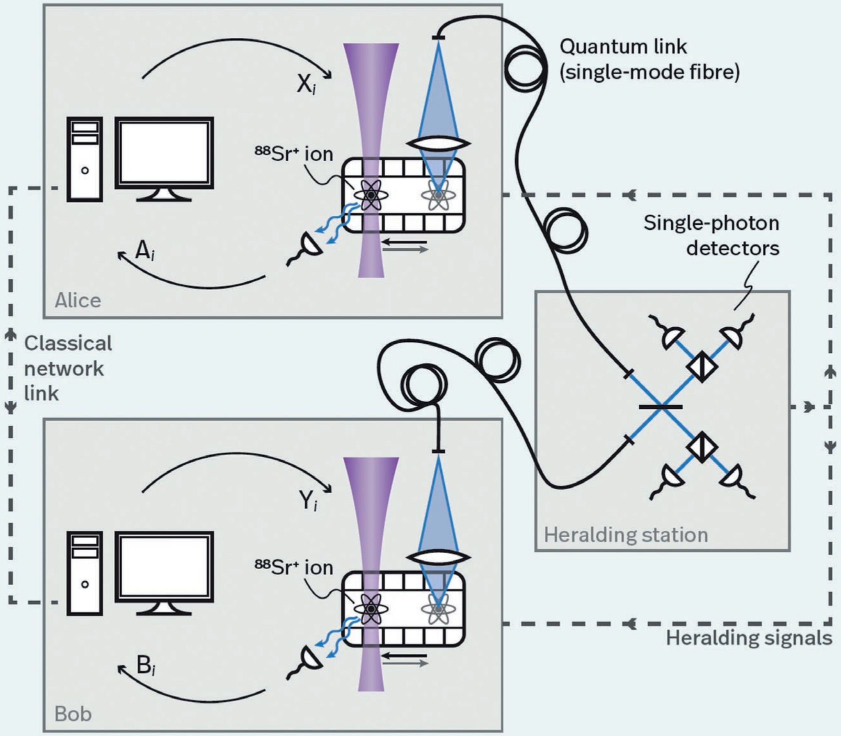
Experimental quantum key distribution certified by Bell's theorem

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 with theorists from Paris/ ETH Zurich/Geneva/ Lausanne.



Featured Paper

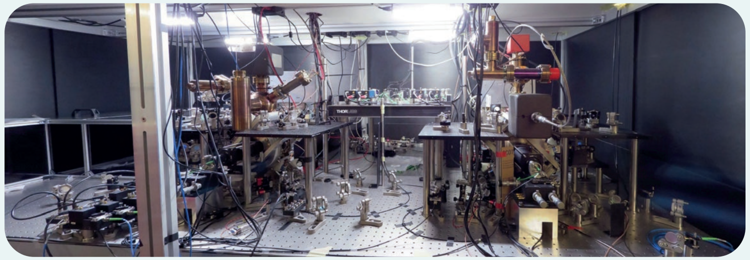
A quantum network of entangled optical atomic clocks

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 $^{88}Sr+$ 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.



Superconducting Circuits

Superconducting circuits are a platform that is very broadly pursued worldwide both in academia and in industry. The technology has matured to such a level that 50-100-qubit scale circuits have been demonstrated by many independent organisations, 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 is carried out by the Hub in collaboration between the Universities of Oxford, Glasgow and Surrey, University College London and Royal Holloway University of London.

Our research focuses 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.

In our pursuit of high-fidelity logic gates we have been working in Oxford with a patented 'tileable' circuit design that uses 3D-integrated control wiring in combination with coaxially symmetric circuits to build 2D grids of qubits [1]. This design is theoretically tileable to large 2D grids of qubits, but several lines of research need to be pursued to make this a reality.

Firstly, we needed to show that the design could scale up without suffering from microwave engineering issues that emerge in circuits with large dimensions [2]. We developed a novel approach to connect the two sides of our circuit enclosures without impacting our circuit coherence and were able to demonstrate state-of-the-art performance in a 4-qubit prototype [3].

Secondly, we needed to develop the technology to incorporate fast magnetic flux control into our architecture to have access to the rich library of logic gates that have been developed in flux-tunable superconducting circuits. We recently developed a novel approach that uses a 'gradiometric' flux control that minimises flux crosstalk and enables high bandwidth local control of each qubit in the grid.

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 also able to quantify the levels of signal crosstalk between circuit elements to be consistent with these errors remaining low as we scale. We have recently managed to extend these findings to a 16-qubit scale, finding similarly promising results. In theoretical work at the University of Surrey, we have 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 show robustness against control pulse amplitude variations.
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 our 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].

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 – cause decoherence and require spectral engineering before reaching the packaged quantum chip. In work at Glasgow, we have done quantitative analysis and obtained experimental data for the noise photon flux through coaxial, filtered wiring. The attenuation of the coaxial cable at room temperature and the noise photon flux estimates for typical wiring configurations were calculated, and compact cryogenic microwave low-pass filters tested at room and cryogenic temperatures up to 70 GHz [6].

Work on quantum annealing using superconducting qubits has been led by our UCL group, supported by fabrication expertise at Glasgow. The overall goal of this work is 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 [7] has identified a scalable approach to speedup in the maximum-independent-set problem which utilises a single XX interaction. Experimental work has focused on design of capacitive YY couplers for flux qubits – the first such couplers were recently shipped from Glasgow to UCL and will be characterised at UCL in the near future.

[1] Rahamim *et al.*, APL **110**, 222602 (2017)
[2] Spring *et al.*, Phys. Rev. Appl. **14**, 024061 (2020)
[3] Spring *et al.*, Science Advances **8**, eabl6698 (2022)
[4] Le *et al.*, arXiv:2110.07737, arXiv:2110.12560 (preprints)
[5] Stehli *et al.*, APL **117**, 124005 (2020)
[6] Danilin *et al.*, EPJ Quantum Technology 9:1 (2022)
[7] Feinstein *et al.*, arXiv:2203.06779 (preprint)

Featured Paper

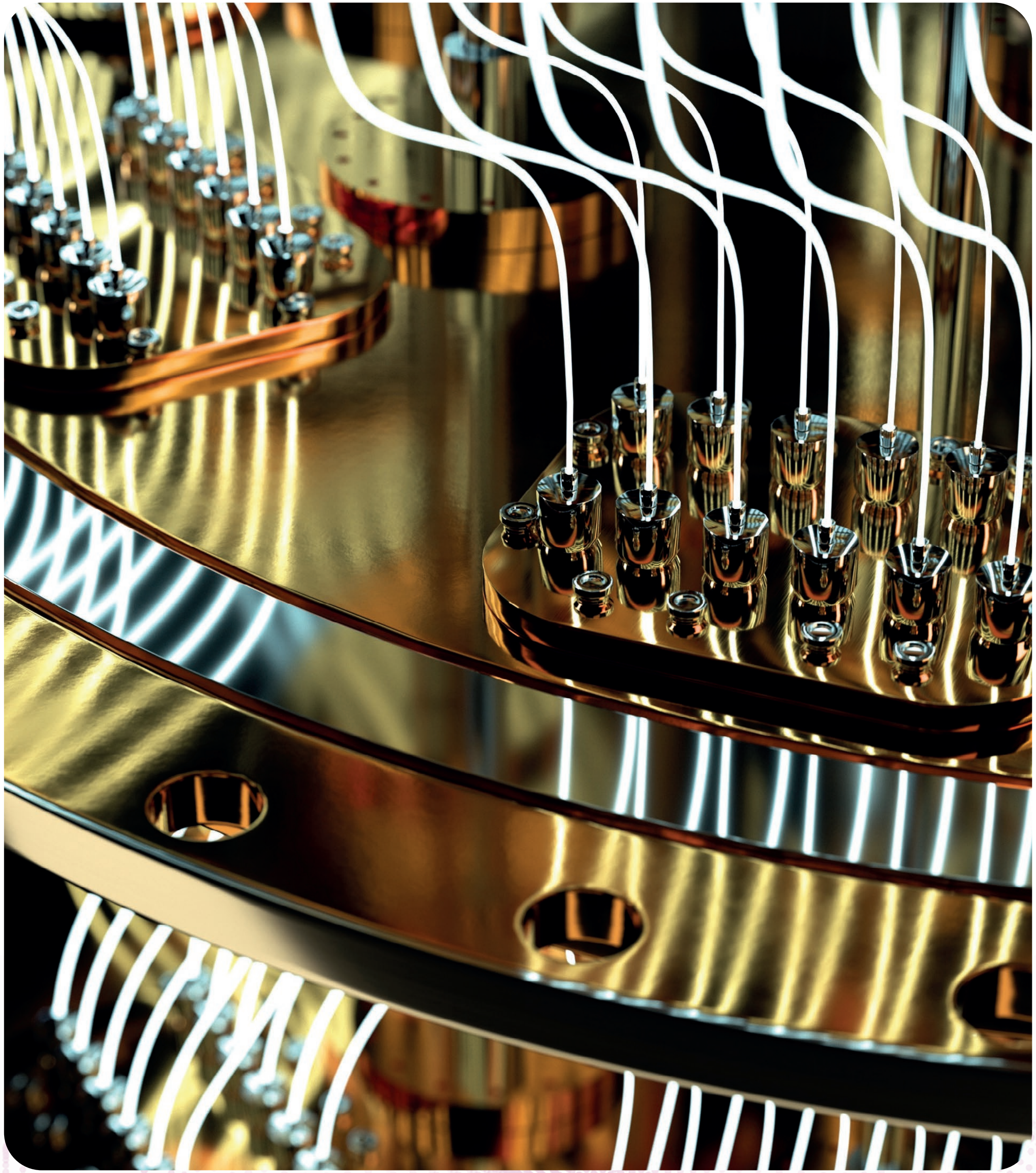
High coherence and low crosstalk in a tileable 3D integrated superconducting circuit architecture

Spring *et al.*, 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.

You can find the paper at:
https://www.science.org/doi/10.1126/sciadv.abl6698

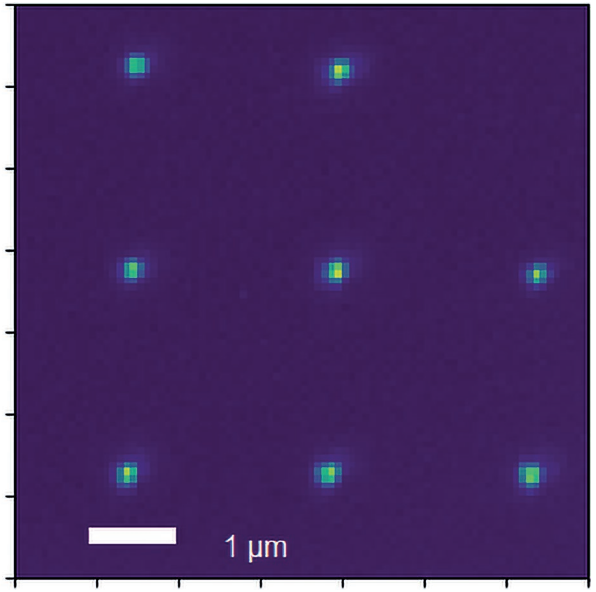


Diamond Chips

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.

The Hub's work in this area focuses 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 is 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.



This image shows fluorescence from an array of single NV defects in a diamond chip produced in our lab. If you look carefully you will see that there is a gap in the array in the top right corner! This is a sign that we have not yet perfected the process – the NV defect we created there was unstable and disappeared after some time, possibly because the interstitial carbon remained too close and fell into the vacancy. Nevertheless, the yield of single NV defects created using this method exceeds 90%, far greater than can be achieved using a thermal annealing process.

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 have been developing 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. We use atomistic models based on density functional theory and molecular dynamics to simulate this physics in ways that facilitate comparison with experimental data.

A second arm of our diamond research involves the integration of NV- defects into optical microcavities, essential for generating entanglement between a large number of electron spins via an optical network. The diamond containing the NV defects is fabricated into a membrane a few micrometres thick, and then high reflectivity mirrors are added either side so that light trapped between them interacts more strongly with the defect. The best design and fabrication method for these microcavities is still under investigation.

In the Hub's third year we have primarily been consolidating the milestone we reached towards the end of the second, in which we succeeded in the deterministic writing of single NV defects using our controlled feedback method into high purity diamond suitable for quantum technologies. This is challenging to achieve because the diamond material in question only has around one nitrogen atom per billion carbon atoms, so a lot of diffusion is generally needed before a vacancy finds a nitrogen impurity to bind to. A new laser was installed which delivers up to 1 million diffusion pulses per second so that formation of an NV centre could be achieved in about 1 minute. (Note - to make a 1 million qubit chip in a practically acceptable timeframe we will clearly have to parallelise this process!). The increased emphasis on diffusion requires finer control in the selection of the laser pulse energy. To address this we have made improvements to the fluorescence monitoring which eliminates background signals, so that it is now possible to monitor vacancy creation and diffusion directly as well as NV defect formation. These in-situ feedback tools are likely to prove vital for fine-tuning the pulse energies used such that high-quality NV defects can be formed.

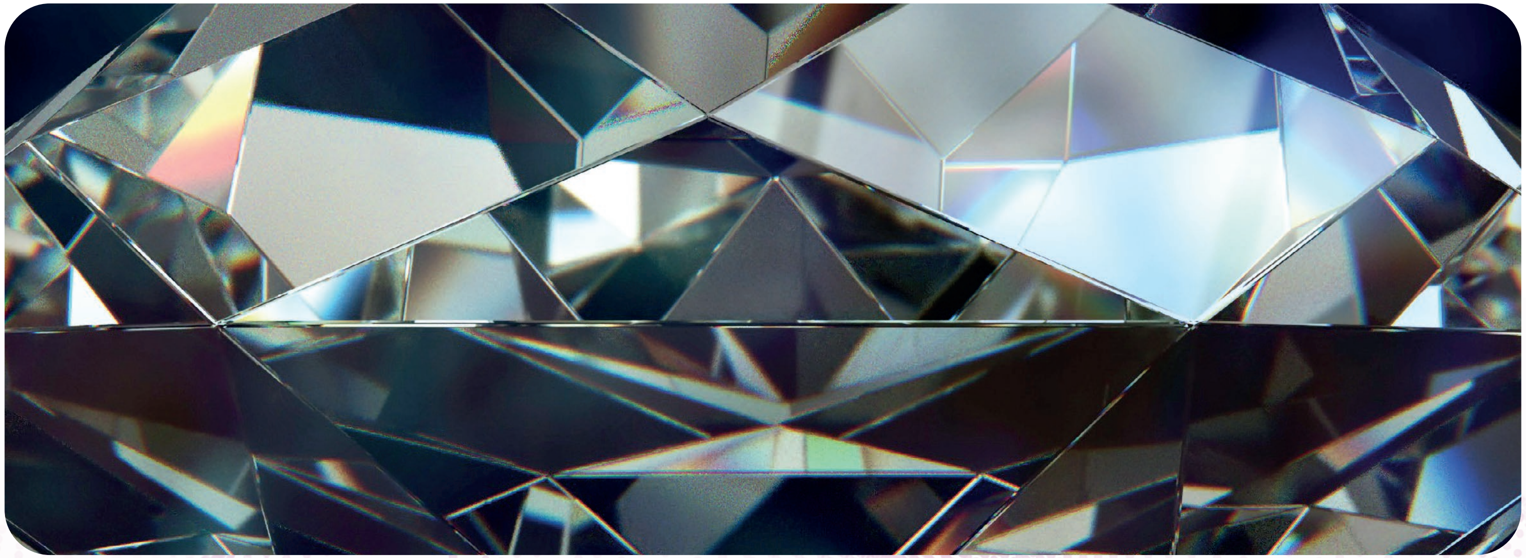
This work brings us closer to our overall goal for our work in this area, which is to achieve a high yield of qubit-quality NV defects in a diamond membrane. In years 4 and 5 of the QCS Hub our diamond research will shift emphasis and team up with our photonics team, to explore the hybridisation of diamond NV defects with photonic chips.

Featured Paper

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

Y.-C. Chen et al, 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.



Photonics

The Hub's work on photonics for quantum computing takes place at the universities of Bristol, Bath, Cardiff, and Imperial College London.

Our teams at Bristol and Imperial are largely working on developing quantum simulators using mature technologies - such as integrated photonics and optical fibres - to address problems related to molecular dynamics, that will one day allow us to design new materials and cleaner sources of fuel.

At Bath and Cardiff, Hub researchers are developing photonic technologies enabling the interface of single photon sources with quantum memories. They are working towards ultra-tunable frequency conversion of quantum dot emission, allowing compatibility with vapour-based atomic quantum memories.

The Hub's Photonics work is led by Anthony Laing, Professor of Physics and Co-Director of The Quantum Engineering and Technology Laboratories at the University of Bristol.

Photonic quantum simulators

One of the most exciting applications of quantum computers is in quantum simulation. Modelling the dynamics of quantum systems is intractable on classical hardware, but by mapping to some other controllable quantum system, efficient, faithful simulation is possible.

Gaussian Boson Sampling (GBS) is a technique which involves interfering squeezed states of light in an interferometer and measuring photons at the outputs. Depending on what interferometer and states of light are used, the output statistics can be used to sample Franck-Condon factors for vibronic transitions of molecules. GBS also provides speed-ups in performing certain tasks in graph theory such as searching for dense subgraphs and max cliques which find several applications in computation and simulation.

Progress

- **Photon sources and state generation protocols**
  - Tasks in photonic quantum information processing require high quality non-classical states of light. Hub researchers at the University of Bristol are developing novel sources of pure squeezed light suited to GBS protocols using coupled resonators and has developed novel protocols for photonic GHZ state generation [1].
  - Photon loss is the primary source of decoherence for quantum photonic technologies. The University of Oxford and Imperial College are working together to develop interstitial integrated photonic components to mitigate photon loss from high-gain squeezed light sources based on ppKTP waveguides [2]
- **Gaussian boson sampling**
  - For more general operations on multimode Gaussian states, additional operations such as displacements are needed to realise applications such as simulating molecular vibronic spectra and measuring the similarity of graphs. Imperial performed the first demonstration of GBS with displacements [3] using two squeezed states and coherent state as inputs into a 15x15 multiport interferometer on a silicon photonic circuit.
  - GBS can provide a speed-up for certain tasks in graph theory. Imperial used a 20-mode time-bin GBS device to search for dense sub-graphs of size three and four in a 10-node graph [4]. The task of finding dense sub-graphs has several applications in studying biological networks, communities in social networks, and fraud detection.
- **Large-scale devices**
  - The ability to correct errors in quantum computation is a key step on the road to universal machines. Bristol previously used a silicon photonic chip to experimentally demonstrate error-protection protocols on entangled states of up to eight qubits [5]. A larger chip with a similar architecture and improved photon sources is now being tested to target simulation tasks involving 18 qubits.
- **VQE experiments**
  - Variational quantum algorithms are a leading candidate for demonstrating near-term applications of quantum devices. Preparing and optimising an efficiently parametrised quantum state gives a route to estimating the ground state energy of molecular systems in quantum chemistry. Bristol is using a silicon photonic chip to experimentally estimate these quantities for a variety of chemical systems.

Deterministic emitters and frequency conversion

Highly efficient single-photon sources can be the cornerstone of a variety of quantum technologies. At the same time quantum dots are a promising platform for generating many high-quality photons, but their emission wavelength is typically not compatible with telecom fibres or atomic memories.

In Cardiff University we are working on photonic devices that not only have high internal efficiency, but also can deliver photons on demand into a fibre. This will further enable the work from the University of Bath that can convert these photons from 920 nm to 1550 nm, allowing long-distance transmission of photonic qubits by fibre.

Progress

- **Quantum dots**
  - Hub researchers at Cardiff University have developed a process that creates devices with efficiencies comparable with the state of the art, and beyond this reducing the rate of parasitic losses by 40%. The processing yield allows for the creation of 100000 devices/week.
  - A curved silica nanolens on the top of the micropillar sculpts the mode to improve coupling into a single mode fibre. These optically driven devices have already achieved five times higher collection efficiency into fibres, by transitioning from a single mode to a few-mode fibre.
  - This few-mode fibre may be returned to a single mode using established mode-conversion techniques, delivering 10s of millions of indistinguishable single photons per second, when driving the system at 80 MHz.

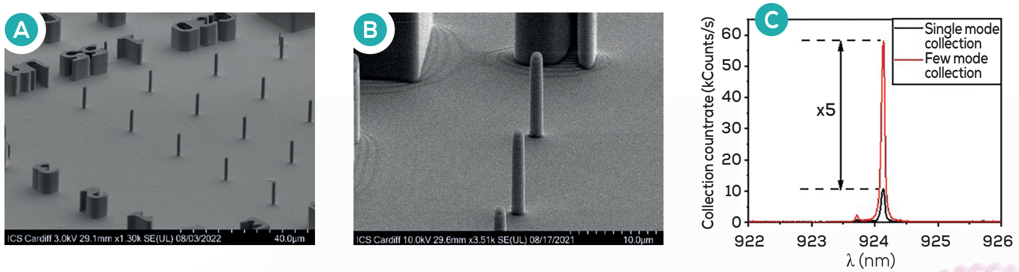


Fig.1 A Electron microscope image of the fabricated structures B Nanolens on top of a micropillar C Under identical collection and excitation conditions a 5x increase in collection efficiency is observed when moving from single mode fibre (780HP) to few-mode fibre (SMF28).

- **Frequency conversion**
  - At Bath, we have successfully demonstrated ultra-tunable wavelength conversion of photons by Bragg-scattering four-wave mixing in fibre in collaboration with the National Research Council (NRC) in Ottawa. Bath fabricated photonic crystal fibre with group velocity that is symmetric over a large frequency range enabling single photons from a range of hundreds of nanometres to be converted to and from the telecoms C-band in just one fibre.
  - This has the potential to be used as a universal "quantum frequency interface" between a variety of network nodes and can encompass Cardiff's quantum dot emission wavelengths around 930 nm. The capabilities of this frequency conversion technique were demonstrated in labs at the NRC, converting heralded single photons from 1550 nm to any wavelength within a range of 1250 – 1450 nm.
  - Bath are also working towards optical switching in a doubly resonant rubidium-filled ring cavity at quantum memory wavelengths around 780 nm. We have designed and built a stabilised ring cavity containing a Rb vapour cell and observed two-photon absorption between counter-propagating strong control and weak signal fields. The experiment is now being optimised to enable the implementation of optical switching with high speed, low loss, and at low control powers.

[1] PRL 126, 230504 (2021), NJP 24, 013023 (2022)
[2] Sun et al., Light Sci Appl 11, 214 (2022)
[3] Thekkadath et al., PRX Quantum 3, 020336 (2022)
[4] Sempere-Llagostera et al., preprint arXiv:2204.05254 (accepted in PRX)
[5] Nat Phys 17, 1137 (2021)

Featured Paper

The boundary for quantum advantage in Gaussian boson sampling

Bulmer et al., Sci. Adv., 8 (4), eabl9236 (2022)

- G GBS provides a route to demonstrating photonic quantum advantage, through the difficulty of sampling photon numbers from an entangled multi-mode Gaussian state. Experiments from USTC in China claimed quantum advantage in 2020 and 2021. In a collaboration between Bristol, Imperial, and HP Enterprise, new classical algorithms were that drastically reduced the runtime for simulating these experiments on a supercomputer. The algorithm has been used to benchmark the most recent quantum advantage experiments by Canadian start-up Xanadu.
- A further speed-up in the classical simulation time is also expected by considering the distinguishability of input squeezed states in the USTC experiment. Work is underway at Imperial to supplement the new framework for loop-Hafnian algorithms with distinguishability and estimate the classical run-time.

Silicon Quantum Processors

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 onto a single chip. QCS Hub researchers are exploring how the same technology can also be used for quantum computing. Our work package 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.

The key strengths of silicon spin qubits are that:

- CMOS is a proven platform to produce billions of devices per chip with high yield and reproducibility
- Integration between quantum devices and classical control is possible on the same chip
- Long coherence times in the solid state are possible (seconds for the electron spin, and hours for the nuclear spin)
- Fault-tolerant fidelities, exceeding 99.5% for both single and two-qubit gates and exceeding 99% for measurement are possible
- Fast gate speeds with single and 2-qubit gates have been demonstrated in ~100 ns
- An inter-qubit spacing of currently ~100 nm in silicon qubits means that a density of 10^7 - 10^8 qubits per cm^2 could be achieved

Our work in this area focuses on two main goals: developing qubits made in CMOS foundries and on-chip qubit transfer (qubit shuttling). Since the launch of the QCS Hub we have 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 300-mm 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. 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). [Ciriano et al., PRX Quantum 2, 010353 (2021)]

Also in 2021, we demonstrated measurements of an ambipolar device in which we could reconfigurably define, with the same electrodes, double quantum dots with either holes or electrons. We used gate-based reflectometry to sense the inter-dot charge transition of both electron and hole double quantum dots, achieving a minimum integration time of 160(100) μs for electrons (holes). This work was selected for the cover image in *Applied Physics Letters* [Duan et al, APL 118 164002 (2021)].

Earlier, in 2020, we developed a way to scale the coupling between qubits in silicon nanowires in 2D, using a floating metal gate that connects two separate nanowires. We used this to enable a quantum dot in one nanowire to sense the state of a quantum dot in another. This research opens a potential route to 2D scaling of quantum dot arrays across nanowires. [Duan et al., Nano Lett 20, 7123 (2020)]

Alongside this hardware work, our researchers have also explored resource estimation for quantum simulation. In the NISQ era, one possible task we can perform without quantum error correction using NISQ machines is the variational quantum eigensolver (VQE), due to its shallow depth. However, we found that implementing a 50-qubit Hubbard model VQE on a NISQ machine would potentially summer for major runtime challenges. We proposed a parallelisation approach called 'multicore NISQ' which lends itself to a silicon implementation due to the high qubit density. [Cai, Phys. Rev. Applied 14, 014059 (2020)]

In 2021, the team used deep learning to understand and control qubit noise environment. Understanding the environment surrounding quantum systems is key to being able to use them as quantum sensors or qubits, but doing so accurately is challenging using traditional mathematical and experimental techniques. We showed how machine-learning techniques and specifically neural networks can be used to infer the qubit environment accurately using only simple and readily performed experimental measurements. This is important because it allows the design of bespoke control sequences to protect fragile quantum states from their particular environments for much longer than would otherwise be the case. [Wise et al., PRX Quantum 2, 010316 (2021)]

Over the next year we will focus on the building blocks for dense, low-cost qubit architectures, concentrating on scalable CMOS-compatible unit cells for universal fault-tolerant quantum computing. We will also explore opportunities for new collaborations in areas such as CMOS cryogenic electronics for qubit control and readout.

Featured Paper

Using deep learning to understand and control qubit noise environment

Wise et al. PRX Quantum 2, 010316

Understanding the environment surrounding quantum systems is key to being able to use them as quantum sensors or qubits, but doing so accurately is challenging using traditional mathematical and experimental techniques. We showed how machine-learning techniques and specifically neural networks can be used to infer the qubit environment accurately using only simple and readily performed experimental measurements. This is important because it allows the design of bespoke control sequences to protect fragile quantum states from their particular environments for much longer than would otherwise be the case.

Cold Atoms

Cold neutral atoms offer an exciting alternative approach to quantum computing and simulation, being based on individual atoms trapped and manipulated with laser light and microwaves. There are two main platform classes built using neutral atoms: Analogue quantum simulators with neutral atoms moving in potentials made of laser light; and tweezer arrays, where atoms are individually trapped and manipulated either as individual qubits with digital quantum gate operations, or in an analogue fashion with the qubits acting as individual spins. The primary upside of both these platforms over other means of implementing quantum computing and simulation is in the ease with which we can control large numbers of identical qubits.

Leading systems internationally currently reach well over 1000 particles when used for analogue quantum simulation, and over 250 when trapped individually in tweezer arrays. The biggest challenges for these platforms are in realising either high-fidelity and fast gate operations for digital quantum computing, or in realising highly-calibrated, programmable local control for analogue quantum simulation.

For example, by loading cold atoms in standing waves of laser light, we can realise an optical lattice, or a crystal potential in which the atoms move. In such systems, we generally have separate control of the potential landscape for the atoms and the interactions between atoms. These setups can be used to build models of electrons moving in solid-state crystals, from which we can learn or test the building blocks of our understanding of modern solid-state materials, involving strongly interacting electrons. 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, and by implementing them in the laboratory we can observe their properties and effectively solve the corresponding models. The challenges are threefold: 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 so that the solutions are reliable; and to understand how to make use of these to extract useful information beyond what can be accessed through calculations on classical supercomputers.

In the QCS hub, we combine experimental and theoretical teams to address these key challenges. We have experimental teams from the University of Strathclyde (led by Stefan Kuhr) and the University of Cambridge (Ulrich Schneider), who are developing and testing individual control of cold atoms in optical lattices, manipulating the initial states for atoms and the potential landscape in which they move by using spatial light modulators and optical tweezers, which impose a potential on top of an existing optical lattice. In addition, we have two theory teams, led by Andrew Daley (University of Strathclyde) and Dieter Jaksch (University of Oxford). They are exploring the calibration and control requirements for attaining a practical quantum advantage with these systems over known classical calculation methods, and exploring potential use-cases of these systems as quantum co-processors to classical supercomputing calculations – especially with applications in materials science. Associated with our cold atoms work we also have a Partnership Resource Fund (PRF) project, led by Jonathan Pritchard (University of Strathclyde). This opens up the other neutral atom platform mentioned above, with individual atoms trapped in tweezer arrays. As well as connecting to a potential digital platform, these offer the possibility for mapping optimisation problems onto neutral atoms in the near term. The PRF project is exploring example applications of these systems when running in an analogue mode.

In the Strathclyde experiments, we have optimised the use of a spatial light modulator (SLM) to create programmable well-calibrated potentials for cold atoms in optical lattices. Constructing an optimized method to detect the phase front of an SLM using interference of wave fronts reflected from parts of the SLMs, together with direct feedback allows us to generate light patterns with about 3% rms error compared to target images controllable on a micrometer length scale. We have demonstrated flat and periodic potentials, suitable for a variety of lattice geometries, and integrated this into a new bosonic quantum-gas microscope setup. This allows us to generate light potentials at different wavelengths, for site-resolved addressing of atoms and local control over spins, as well as the generation of repulsive potentials. In our atomic Mott-insulators, which we image with single-atom resolution, we can now produce clearly defined regions with a specific atom number next to regions where no atoms are present. We are currently studying heating effects and work towards using dynamically varying light potentials. The Cambridge team has developed a complementary new apparatus for realising Kagome lattice potentials, in combination with optical tweezers. These allow for alternative forms of local control over the lattice potential, which are particularly useful for generating arbitrary initial configurations for the locations of atoms. They have already realised both Mott Insulator states and negative temperature states of delocalised atoms in this Kagome lattice geometry, and are further progressing intensity stabilisation and magnetic field control.

On the theory and software side, we have made progress both in tools to extend the applications of quantum simulators with cold atoms, and to improve our theoretical tools for benchmarking and verification of these analogue devices. The group at Strathclyde has explored the hardware requirements for quantum advantage in these systems, as well as generalisations of randomised benchmarking to analogue devices (in collaboration with hub partners in Edinburgh, and WP7). We have also explored regimes of fast scrambling of quantum information, specifically for the purpose of rapidly generating of entangled resource states. These could extend applications of entangled arrays of cold atoms to metrology and sensing. We have separately developed new methods to speed up adiabatic processes by combining counter-diabatic local driving with optimal control techniques. The Oxford theory team have explored the minimum hardware requirements for hybrid quantum-classical Dynamical Mean-Field Theory calculations, in which we have developed a re-compilation tool for systematically reducing the complexity of quantum circuits. We have developed this further such that it can generate the re-compiled circuit without using a classical computer for simulating the circuit. Separately, we have published work on analysing and simulating turbulent fluid flow with a quantum-inspired approach.

Featured Paper

Propagation of errors and quantitative quantum simulation with quantum advantage

S. Flannigan et al., Quantum Science and Technology 7, 045025 (2022)

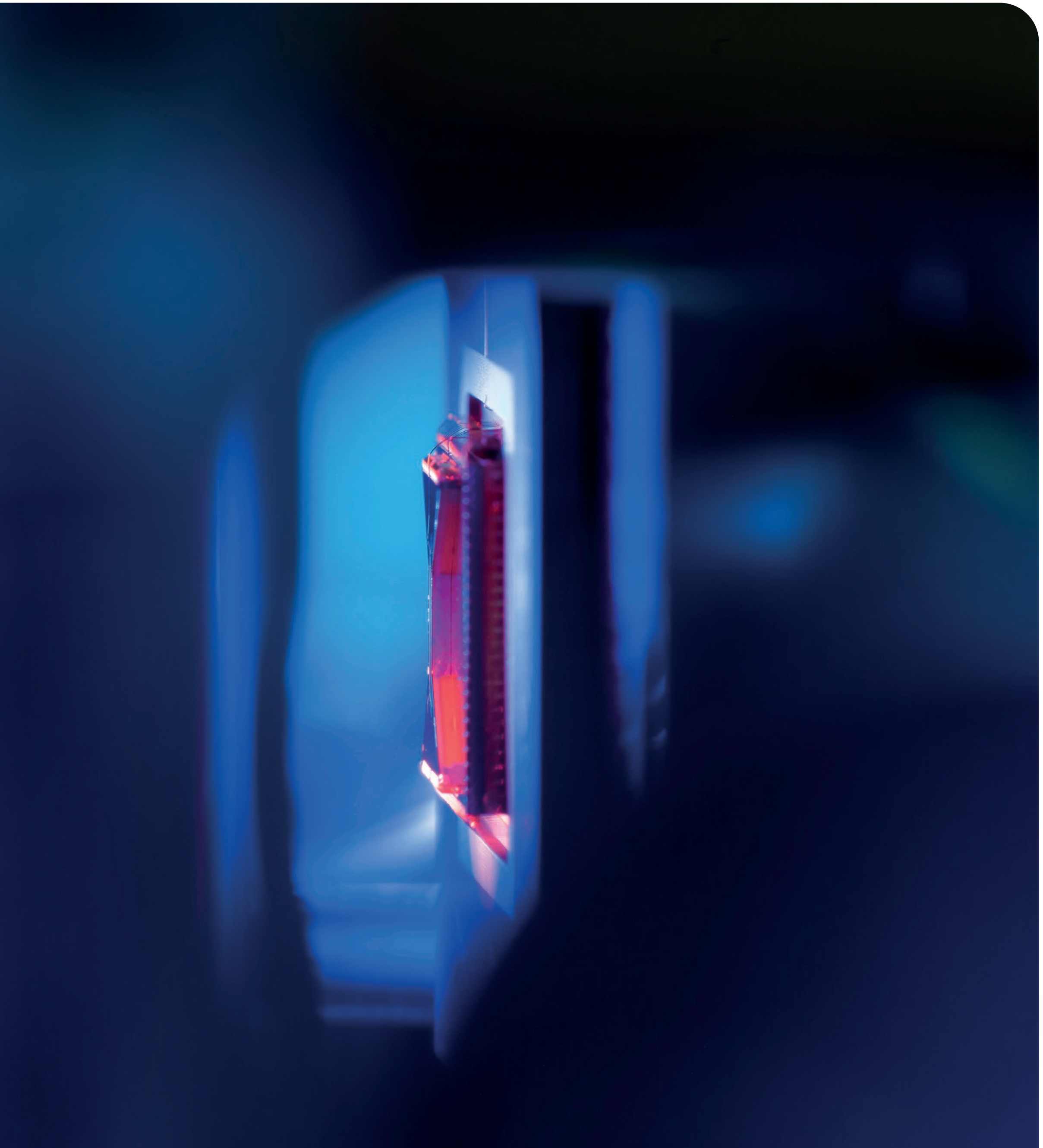
In our paper [S. Flannigan et al., *Propagation of errors and quantitative quantum simulation with quantum advantage* Quantum Science and Technology 7, 045025 (2022)], we have analysed the accumulation of errors in analogue devices, taking quantum quench dynamics implemented with atoms in optical lattice or trapped ions as examples that are exponentially difficult to compute with known classical methods. We conclude that for models that are directly engineered in experiments, regimes of practical quantum advantage are attained with current hardware. We also compare this with the hardware requirements to reach the same level of accuracy with future fault-tolerant digital quantum simulation. This work also informed a Nature perspective [A. J. Daley et al., *Practical quantum advantage in quantum simulation,* Nature 607, 667 (2022)].

The EPSRC funds a Prosperity Partnership project between Strathclyde University and M Squared Lasers that aims to develop a new platform for quantum computing based on scalable arrays of neutral atoms that is able to overcome the challenges to scaling of competing technologies. The QCS Hub is proud to be sponsoring a Partnership Resource Funding project that connects to this PP programme as another demonstration of the successful connections between the UK research activities in this field.

Software and applications research at the hub

Hardware is just one piece of the quantum computing puzzle. The Hub is also carrying out research into the areas of quantum software and applications. Our work in the areas below is examined over the following pages:

- Verification, Validation & Benchmarking
- Architectures, Control & Emulation
- Algorithms & Fundamentals
- Applications



A quantum network node in the Ion Trap Quantum Computing group | David Nadlinger

Verification, Validation and Benchmarking (VVB)

Part of the Hub's research focusses on the importance of verification, validation, and benchmarking. We're developing a set of tools tailor-made for various hardware to ensure our target applications are implemented correctly. We both certify the device fabrication, as well as verify the computation, taking into account the noise.

This is important because when the number of qubits goes beyond a hundred, one cannot simulate the quantum process classically, and that's when we are ready to deploy our tools to provide end users with the appropriate standard of accuracy and reliability for various different platforms.

Enforcing the correct functioning of a quantum device, using the minimum amount of resources, while making as few assumptions.

GOAL:
Efficient validation methods suitable for
- NISQC Machines towards quantum advantage validation
- Quantum Simulation
- Universal FT Quantum Computer

Tailor made for specific Applications or Resources

Technical Progress So far:

We have explored various directions to deal with noise. From randomised benchmarking, to error mitigation, from lightweight detection all the way to full-fledged quantum verification. Our guiding principle in reinventing these fields are a close collaboration with the hardware developers exploring realistic noise model to ensure our theoretical tools could assists scaling up device fabrication and design. Of course there remain many gaps in between to fully connect theory and experiment and the battle is still on. Below we summarise few such results obtained through our full feedback loops 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 inversion step. Further, it allows for 'gate synthesis' to be able to tailor-made the scheme for the native gates of a given platform. To expand further our practical approaches we also explored a lightweight detection scheme for the error occurring in the implementation of a target unitary circuit. It considers two cases: one where the target unitary differs from the ideal unitary in only one gate. In this case the protocol identifies the error and thus allows for the correction. In the second case, when the target unitary to be implemented is constructed from purely Clifford gates, then there is no assumption on the number of gates which can be faulty. The protocol allows for only a constant run of the noisy unitary to identify the fault and thus to be able to correct it [2]. To enable not only detection but also mitigation of noise, we have fused quantum verification technique that we have been pioneering over the decades [3] to design for the first time a scalable error mitigation scheme without any adhoc assumptions that currently all other schemes are suffering from [4]. To guide the hardware developer in their fabrication we have pioneered a simulation-based technique to benchmark specific quantum protocols to identify concrete parameters for the components that will deliver the expected performances [5]. In particularly focusing on specific building blocks we have analysed the performance of the quantum Fourier transforms and individual measurements on noisy devices [6,7].

Many of our constructions are guided by the verification framework that was developed over the years within the hub naturally we revisited this framework taking into accounts all the hardware limitations and requirements to achieve a recent breakthrough to demonstrate the first practical verification scheme for NISQ Devices completely closing the previous known gaps between theory and implementation [8]. A general framework is now obtained that will further enhance all the schemes for benchmarking and mitigation that is built upon this approach as well [9].

Occupying this in between space, expanding theoretical toolkits while remaining close and aware of hardware development we explored new territories particularly important for network architectures for distributed date centre serving several multi 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 network [10]. We also designed a practical verified multi partite delegated computing scheme as the blueprint for quantum computing services in the cloud [11].

[1] Derbyshire, Ellen, et al. "Randomized benchmarking with stabilizer verification and gate synthesis." *arXiv preprint arXiv:2102.13044 (2021).*

[10] Colisson, Léo, Frédéric Grosshans, and Elham Kashefi. "Non-Destructive Zero-Knowledge Proofs on Quantum States, and Multi-Party Generation of Authorized Hidden GHZ States." *arXiv preprint arXiv:2104.04742 (2021).*

[4] Mezher, Rawad, James Mills, and Elham Kashefi. "Mitigating errors by quantum verification and postselection." *Physical Review A 105.5 (2022): 052608.*

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[8] Leichtle, Dominik, et al. "Verifying BQP Computations on Noisy Devices with Minimal Overhead." *PRX Quantum 2.4 (2021): 040302.*

[9] Kapourniotis, Theodoros, et al. "A Framework for Verifiable Blind Quantum Computation." *arXiv preprint arXiv:2206.00631 (2022).*

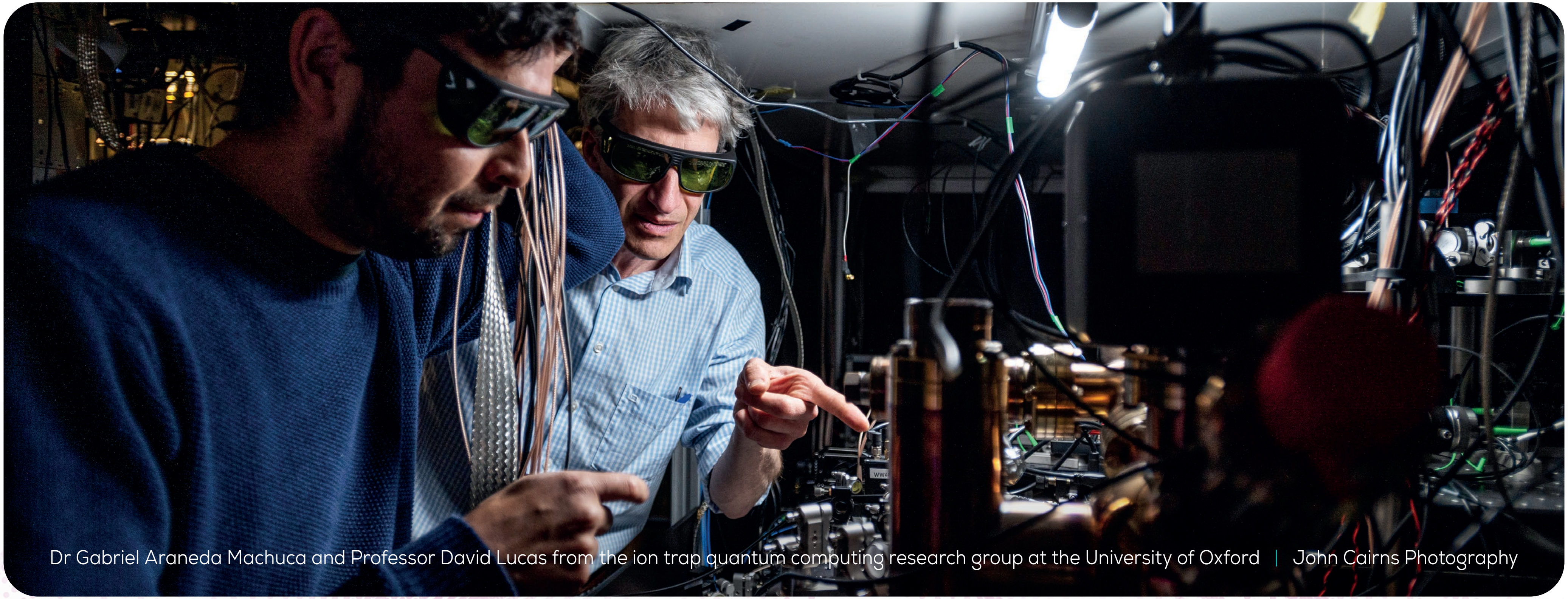
[11] Kapourniotis, Theodoros, et al. "Delegating Multi-Party Quantum Computations vs. Dishonest Majority in Two Quantum Rounds." *arXiv preprint arXiv:2102.12949* (2021).

[3] Ferracin, Samuele, Theodoros Kapourniotis, and Animesh Datta. "Accrediting outputs of noisy intermediate-scale quantum computing devices." *New Journal of Physics* 21.11 (2019): 113038.

[6] All quantum measurements are asymptotically equivalent
N Linden, P Skrzypczyk
arXiv preprint arXiv:2203.02593
2022

[7] Average-Case Verification of the Quantum Fourier Transform Enables Worst-Case Phase Estimation
N Linden, R de Wolf
arXiv preprint arXiv:2109.10215

[2] Lightweight detection of a small number of large errors in a quantum circuit
N Linden, R de Wolf Quantum 5, 436



Dr Gabriel Araneda Machuca and Professor David Lucas from the ion trap quantum computing research group at the University of Oxford | John Cairns Photography

Architectures, Control and Emulation (ACE)

As part of our work on the software behind quantum computing we are investigating a number of different areas. Several closely related themes are combined in our work, in the area of architectures, control and compilation, and emulation - known under the acronym ACE.

- Architectures: Understanding the theory of how our qubits should be arranged, the levels of connectivity, the clock speed relevance versus noise, etc.
- 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.
- Emulation - using today's computers to simulate small quantum computers.

Looking at the last of these, emulation, we can see how it enables work within the other themes.

Emulation – Making conventional computers pretend to be quantum computers!

The ideal way to test out an idea for a quantum algorithm, or an error mitigation technique, is of course to try it on a real quantum system! As more and more prototype quantum devices are put online this becomes a real possibility. But in the current environment, the devices available are limited in scale, oversubscribed, and may suffer very severe levels of noise. Moreover, a given quantum device will have specific noise and connectivity properties that are 'baked in' whereas an algorithm designer may wonder how their idea will perform on diverse systems – or systems that don't yet even yet exist. For these reasons it is vital to have the power of emulation: Using convention computer hardware to accurately simulate a quantum machine. So we made QuEST and QuESTlink.

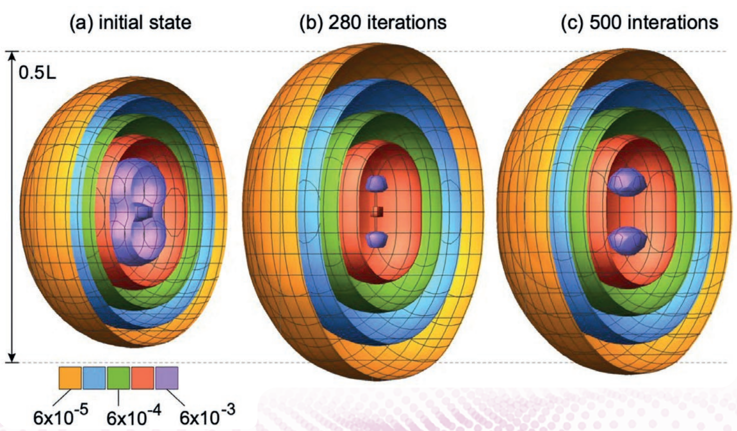
The Hub has supported the development of the QuEST family of tools. QuEST stands for Quantum Exact Simulation Toolkit. It is one of the most powerful emulation systems in the world – and importantly, it is open source so that researchers everywhere can use it. At its heart QuEST is a C and C++ simulation framework, which supports a rich set of operations like Pauli gadgets, multi-qubit general unitaries, density matrices, general Kraus maps. QuESTlink integrates these high-performance facilities into Mathematica, for an intuitive and usable interface.

QuEST and QuESTlink 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.
More information on core QuEST can be found at https://quest.qtechtheory.org while details about the Mathematica version can be seen at:
https://questlink.qtechtheory.org

Meanwhile the latest member of the QuEST family, tentatively titled pyQuEST, provides a way for python programmers to access all the power of compiled c-code from their favourite environment.

Here's one of the most recent uses of QuEST, from the paper "Grid-based methods for chemistry simulations on a quantum computer". QuEST was used to emulate quantum computers of up to 36 perfect qubits, in order to investigate how effective quantum computers will be as tools for chemists. The challenge is to model molecules and their dynamics – which of course is a deeply quantum problem – using a quantum algorithm.

In the figure, we see the way that a small quantum computer would model a Helium molecule – we observe the twin-peaked charge distribution because of helium's two electrons, and we note that the molecule is in an excited state that makes it stretch and contract.



QuEST enables a lot of other research in the ACE work package. Here are two related papers which looks at the Architectures and Control themes.

Featured Paper

Exponential Error Suppression for Near-Term Quantum Devices

Bálint Koczor, Phys. Rev. X 11, 031057

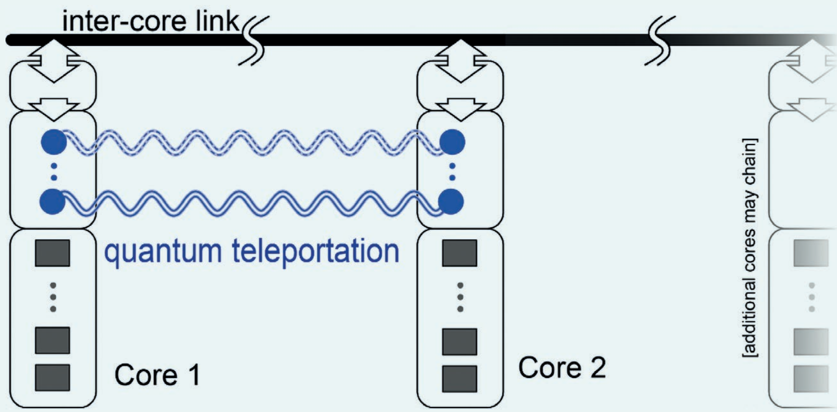
While quantum computers promise to solve problems of key importance, current machines suffer from hardware noise. Since powerful error-correction techniques are out of reach in the near term due their daunting resource requirements, we need to resort to so-called error mitigation techniques.

A recent theoretical breakthrough proposes 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'** [B Koczor, PRX, 11 (2021) 031057]. The approach may be suitable for relatively near-term quantum technology as it only needs a few interlinked quantum processors.

Featured Paper

Multicore Quantum Computing

Hamza Jnane et al, arXiv:2201.08861 [quant-ph]



Recent work by H Jnane et al proposes a multicore architecture as a promising architecture. Multiple quantum cores are connected by an inter-core, quantum communication link, making the architecture well-suited to perform the derangement-circuit error mitigation.

Detailed numerical modelling of the multicore architecture reveals that error characteristics in today's state-of-the-art experiments with semiconductor systems can suffice to realise the idea, which then in turn supports a whole range of applications for noisy, intermediate scale (NISQ) quantum machines

Dr Fabian Pokorny and Andres Vazquez-Brennan from the ion trap quantum computing research group at the University of Oxford | John Cairns Photography

Algorithms & Fundamentals

Providing a theoretical underpinning for the full portfolio of the Hubs research is our work on algorithms and fundamentals. These areas are focused on long-term questions around the power and nature of quantum computation and information, designing new algorithms for key mathematical and physical problems and also with developing techniques/algorithms for near-term hardware. The Hub has published a number of high-impact papers across these themes which demonstrate the breadth and quality of our work in this area.

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].

"Computational Complexity of the Ground State Energy Density Problem" [2], a paper by researchers Toby Cubitt and James Watson, has made significant impact in the theoretical computer science community. 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* which, together with the IEEE Symposium on Foundations of Computer Science (FOCS), are the major conferences in theoretical computer science.

The paper is in some sense a culmination of work in a key theme of the Hub, namely, concerning the computational complexity (difficulty) of key physical questions. The paper concerns 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. 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. The ground state energy density problem is unusual, in that it concerns a single, fixed Hamiltonian in the thermodynamic limit, whose ground state energy density is just some fixed, real number. The only input to the computational problem is the precision to which to estimate this fixed real number, corresponding to the ground state energy density. Hardness of this problem for a complexity class therefore implies that the solutions to all problems in the class are encoded in this single number (analogous to Chaitin's constant in computability theory). The paper gives rigorous bounds for the type of question most commonly encountered in condensed matter physics, which is typically concerned with the physical properties of a single Hamiltonian in the thermodynamic limit.

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 $d \geq 2$, 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.

The theme of algorithmic techniques for near-term quantum devices has been a key one in the Hub's theoretical work. The process of measurement is fundamental to quantum mechanics, and, along with entanglement, its defining feature. The textbook measurement process is the ideal von Neumann measurement. But in practice this rarely, if ever, can be performed; real measurements are lossy, noisy, or otherwise imperfect. It has long been understood that the most general type of physical measurement process is much broader, even than this.

As well as ideal and imperfect measurements, generalised measurements include, for example, processes where the number of outcomes is greater that the dimension of the system. In *"How to use arbitrary measuring devices to perform almost perfect measurements"* [4], the Hub's Noah Linden, alongside Paul Skrzypczyk have now shown that, unexpectedly, if sufficiently many uses are made of any non-trivial quantum measurement, then it can reproduce any other quantum measurement arbitrarily well. In this sense all measurements are equivalent, and indeed at finite rate of interconversion, asymptotically. The paper also shows that the error in reproduction drops off exponentially fast in the number of uses. This means that not only are the results of fundamental interest, but may have practical applications, whereby noisy or lossy measurements can be improved by performing simple protocols involving only a few uses.

The Hub has also been pursuing the broader theme of addressing fundamental questions in quantum information and understanding key primitives. Such a theme is privacy amplification.

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 "Differential Privacy Amplification in Quantum and Quantum-inspired Algorithms" [5] , Elham Kashefi et al. provide privacy amplification bounds for quantum and quantum-inspired algorithms. In particular, this paper shows for the first time, that algorithms running on quantum encoding of a classical dataset or the outcomes of quantum-inspired classical sampling, amplify differential privacy. Moreover, the paper proves that a quantum version of differential privacy is amplified by the composition of quantum channels, provided that they satisfy some mixing conditions.

[1] Cerezo, M. *et al.* Variational quantum algorithms. *Nat Rev Phys* **3**, 625–644 (2021)

[2] J Watson and T Cubitt, Computational Complexity of the Ground State Energy Density Problem, arXiv:2107.05060 [quant-ph]

[3] Linden, N., Montanaro, A. & Shao, C. Quantum vs. Classical Algorithms for Solving the Heat Equation. *Commun. Math. Phys.* **395**, 601–641 (2022)

[4] Linden N. and Skrzypczyk P. How to use arbitrary measuring devices to perform almost perfect measurements. arXiv:2203.02593 [quant-ph]

[5] E. Kashefi et al. Differential Privacy Amplification in Quantum and Quantum-inspired Algorithms. arXiv:2203.03604 [quant-ph]

Featured Paper

Exponential Error Suppression for Near-Term Quantum Devices

B Koczor, Phys. Rev. X 11, 031057 (2021)

The Hub post-doc Koczor's paper on "Exponential Error Suppression for Near-Term Quantum Devices" appeared in ***Physical Review X*** and was featured in ***Physics***. Most error correction schemes are too computationally costly to implement on existing machines, as they require encoding a single bit of quantum information into thousands of physical qubits. The complexity of these schemes is prohibitive for existing and near-term quantum computers.

This paper presents a method for side-stepping error correction by reducing errors in the first place. The new method should offer better scaling to larger devices than existing error correction codes. With an independent team involving Google researchers recently proposing a similar scheme, qubit-swapping approaches are gaining momentum as error-reduction solutions for near-term quantum computers, says Koczor.

Dr Sarah Croke at Glasgow University successfully applied for Hub PR Funding for a project to explore quantum machine learning for gravitational wave data analysis. This project illustrates that in the field of algorithm development, future users, particularly those in science, will play an important role.

Applications

Quantum computers have the potential to bring huge potential 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 manufacture 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 study the requirements and performance of promising applications for near to medium-term quantum computers. There are three university groups involved in this work: University College London (led by Prof. Dan Browne), Imperial College London (led by Prof. Myungshik Kim) and the University of Bristol (led by Prof. Anthony Laing).

Prof. Browne's group is exploring quantum algorithms which may have practical applications in near- to medium-term quantum computers, in search of a "killer app" which may push forward quantum computing development. The focus of their study so far has been a quantum algorithm called amplitude estimation. 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.

The algorithm was first proposed in the 1990s, but in a form which is extremely difficult to accomplish without a large-scale fault-tolerant quantum computer. Recently, it was realised that the algorithm could be simplified and achieved with much more modest quantum computational resources. The Hub team at UCL have 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. They are also exploring the potential for quantum computers to improve the performance of optimisation algorithms with diverse applications from the analysis of crystallography data, to the classification of network data.

The Imperial College team, led by Prof. Kim, have investigated methods of improving the performance of near-term quantum computations by developing flexible and powerful error mitigation techniques, which allow the quantum computer's signal to be enhanced without the need for expensive error correction. They have also developed new approaches for the simulation of molecular properties, an important application of quantum computers which could lead to the development of new materials for solar cells, and aid drug design. They found that their algorithmic approach led to a 100-fold improvement in performance, by linking together multiple quantum computations. Prof. Kim's group have also studied how energy transport in molecular systems – an important process in light capture in bio-molecules and solar cells - can be simulated in the presence of noise and studied the role noise plays in the key properties of this phenomenon. Variational Quantum Algorithms (VQA's) are a promising method for application-based hardware benchmarking. Finding a good initial condition, and a suitable ansatz circuit are both active areas of research, and improvements in either will boost the performance of VQA's. Researchers at Kim's group report a new algorithm – Clifford pre-optimisation – that significantly pushes the classical limit of VQA's, thereby minimising the burden on the quantum hardware. This allows for reduced quantum processor time which in turn increases throughout and reduces cost overheads for quantum devices.

Prof. Laing's group at Bristol are focussing on heterogeneous architectures and applications for optical quantum computers where information is represented in pulses of light. Light is a promising platform for quantum computing, since the key elements of a photonic quantum computer comprising light sources, interferometers and detectors, have benefitted from enormous research and development in the telecoms sector. When combined together with functional optical components that are being developed in academia, such as deterministic photon sources, a powerful and scalable platform for special purpose and general purpose quantum computing can be realised. Light can both represent quantum bits, as in general purpose quantum computers, or simulate a quantum wave in certain special purpose quantum computers. Prof. Laing's group are studying how light oscillations can directly represent vibrational oscillations that are centrally important for a number of important chemical reactions. These include the disassociation of water, where vibrational energy can literally shake the molecule apart. Splitting water has hugely important applications in the generation of Hydrogen gas – which can burn as a pollution-free clean fuel. The Bristol team are also studying the fundamental questions of when a photonic quantum computer can give a computational advantage. They have made significant advances in determining where photonic experiments can outperform classical computers in a special purpose algorithm called Gaussian Boson sampling, showing that such experiments will need to be significantly improved from their current status before they can outperform classical simulations in practical tasks.

Featured Paper

The boundary for quantum advantage in Gaussian Boson sampling

J. F. F. Bulmer, et al, Science Advances, Vol 8, Issue 4 (2022)

We investigated a specific type of quantum sampling problem which runs on photonic quantum computers, known as Gaussian boson sampling. The original claim for quantum advantage using Gaussian boson sampling came from an experiment performed by the University of Science and Technology, China (USTC) **https://www.science.org/doi/10.1126/science.abe8770.** They claimed that their experiment would take 600 million years to run on the world's largest supercomputer. However, they based this claim on the best available algorithms from the literature.

When we read their paper, we thought that we would be able to improve upon these claims. The main source of the speedup in our work was to develop a new algorithm which exploits the detectors used in their experiment. The detectors they used can distinguish between 0 photons and 1 or more photons in each detector, but they cannot distinguish between 1 photon and 2 photons, for example. This allowed us to simulate their experiment accurately, whilst also ignoring many of the photons which arrived at the detectors. Being able to ignore these photons leads to big speedups, which for this particular experiment, was a speedup factor of 1 billion.

The challenge to discover and develop use cases and application will require the involvement of end-users and their domain expertise. Two very different illustrations of how the QCS Hub manages to engage those end-users are the extensive activities in the Financial Sector, a long-running project also involving the NQCC, the FCA and Bank of England, BEIS and HM Treasury and all the major UK banks. And as a contrast, the Hub also sponsored a PRF project to explore the application of quantum computing in electronic music and composition in collaboration with Prof Eduardo Miranda and collaborators such as Spotify, InMusic and Rigetti.

User Engagement

The overarching purpose of the QCS Technology Hub is to advance our technologies to support the creation of a thriving quantum information economy in the UK. That has been the case since the start of the original Hub in 2014 and alongside a long and impressive list of technical achievements, it continues to be a principal source of authoritative and independent expertise in the UK.

An eco-system that is both quantum ready and that will play a prominent global role will involve all parts of the QT value chain: enabling technologies, system integration and services, developers, end-users, a skilled workforce, engagement from wider industry, and informed public and policy makers. The Hub has engaged with all of these since 2014. Notable activities in the past have included Industry Days, a UK National Quantum Readiness programme, accessible introductions to various aspects of the technology, funded collaboration projects, contracts with platform providers, international representation, standards promotion and development, policy making input through the Parliamentary S&T Subcommittee and Government Departments, hackathons and public engagement through our joint Hub initiative called Quantum City.

The Hub also plays an active role in the creation of new ventures through the encouragement of entrepreneurship, engagement of the investor community and the promotion of the field to policy makers. In this aspect of the ecosystem the Hub works closely with the Technology Transfer Offices of the UK Universities, supports organisations such as Bristol university's QTEC, Innovate UK and the National Quantum Computing Centre, who each play a very large role in helping to make the new UK quantum companies thrive through networking, co-funding and scaling. As a result of this combined effort we see a growing number of ambitious UK QIT companies developing a variety of platforms and also software and enabling technologies.

The Hub itself is part of this ecosystem that goes beyond industry engagement. We work closely with the other Technology and Skills Hubs, the National Physical Laboratory, STFC and naturally all the sponsors of the UK NQTP including (BEIS, EPSRC, UKRI, KTN, Dstl, NCSC, and MoD).

Outside the UK we maintain close contacts with other national programmes, companies, and research institutions.

Throughout this document we have included brief descriptions of a number of projects that illustrate the breadth of the Hub's connections between our researchers and other organisations in the emerging quantum eco-system. We hope that this encourages others to join the programme and the Hub's dedicated User Engagement team looks forward to hearing from you.

Downloadable Reports

We have produced two reports (with more on the way) designed to help non-expert readers to understand the emerging quantum landscape and the opportunities it presents.

The first 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.

The second is the first of two reports that summarise global activity in quantum technology. It 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.

Both are available to download for free at
https://www.qcshub.org/resources

Outputs (Papers)

A single-crystal diamond X-ray pixel detector with embedded graphitic electrodes.
Bloomer C et al.
J. Synchrotron Rad. (2020). 27, 599-607 | DOI: 10.1107/S160057752000140X

The prospects of quantum computing in computational molecular biology
Outeiral C et al.
WIREs Comput Mol Sci. 2021;11:e1481 | DOI: 10.1002/wcms.1481

QuESTlink-Mathematica embiggened by a hardware-optimised quantum emulator
Jones T and Benjamin S
Quantum Sci. Technol. 5 034012 | DOI: 10.1088/2058-9565/ab8506

Quantum Circuits with Classically Simulable Operator Scrambling.
Blake M and Linden N
Phys. Rev. Lett. 125, 030502 | DOI: 10.1103/PhysRevLett.125.030502

Efficient Qubit Routing for a Globally Connected Trapped Ion Quantum Computer
Webber M et al.
Adv. Quantum Technol. 2020, 3, 2000027 | DOI: 10.1002/qute.202000027

Motional Dynamical Decoupling for Interferometry with Macroscopic Particles.
Pedernales JS, Morley GW and Plenio MB
Phys. Rev. Lett. 125, 023602 | DOI: 10.1103/PhysRevLett.125.023602

Efficient Hamiltonian programming in qubit arrays with nearest-neighbor couplings
Tsunoda T et al.
Phys. Rev. A 102, 032405 | DOI: 10.1103/PhysRevA.102.032405

Understanding High-Gain Twin-Beam Sources Using Cascaded Stimulated Emission
Triginer G et al.
Phys. Rev. X 10, 031063 | DOI: 10.1103/PhysRevX.10.031063

Coherent superconducting qubits from a subtractive junction fabrication process
Stehli A et al.
Appl. Phys. Lett. 117, 124005 (2020) | DOI: 10.1063/5.0023533

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Demonstration of Adiabatic Variational Quantum Computing with a Superconducting Quantum Coprocessor.
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Wan K, Neville A and Kolthammer S
Phys. Rev. Research 2, 043280 | DOI: 10.1103/physrevresearch.2.043280

4-by-4 Integrated Waveguide Coupler Based on Bi-Directional Propagation in Two Single-Mode Waveguides
Weisen M et al.
IEEE Photonics Journal, vol. 13, no. 1, pp. 1-14, Feb. 2021 |
DOI: 10.1109/jphot.2020.3040073

Single-Phonon Addition and Subtraction to a Mechanical Thermal State.
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Phys. Rev. Lett. 126, 033601 | DOI: 10.1103/physrevlett.126.033601

On the Possibility of Classical Client Blind Quantum Computing
Cojocaru A et al.
Cryptography 2021, 5(1), 3 | DOI: 10.3390/cryptography5010003

Hybrid Quantum-Classical Algorithms and Quantum Error Mitigation
Endo S et al.
J. Phys. Soc. Jpn. 90, 032001 (2021) | DOI: 10.7566/jpsj.90.032001

Quantum magic rectangles: Characterization and application to certified randomness expansion
Adamson S and Wallden P
Phys. Rev. Research 2, 043317 (2020) | DOI: 10.1103/physrevresearch.2.043317

Quantum certification and benchmarking
Eisert J et al.
Nature Reviews Physics volume 2, pages 382–390 (2020) | DOI: 10.1038/s42254-020-0186-4

Anomalous Spin-Charge Separation in a Driven Hubbard System.
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Phys. Rev. Lett. 125, 195301 (2020) | DOI: 10.1103/physrevlett.125.195301

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Minimum hardware requirements for hybrid quantum-classical DMFT
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Grid-based methods for chemistry simulations on a quantum computer
Hans Hon Sang Chan et al.
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Differential Privacy Amplification in Quantum and Quantum-inspired Algorithms
Armando Angrisani, Mina Doosti, Elham Kashefi
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Quantum Local Differential Privacy and Quantum Statistical Query Model
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How to use arbitrary measuring devices to perform almost perfect measurements
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Unifying Quantum Verification and Error-Detection: Theory and Tools for Optimisations
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Scalable and Programmable Phononic Network with Trapped Ions
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Outputs (PRF Projects)

The table below lists all the projects that the QCS Hub has funded to date. Several have already completed or are in the final stages of conclusion (eg, confirming final invoices). Several are in implementation stage, where contracts are being concluded.

Project	PRF Category	Status	Lead Investigator	Lead Institution
SQUARE : Scalable QUbit AddREssing	Academic	Project complete	Booth	Oxford
Emulator of noisy near-term superconducting architectures	Academic	Conclusion	Sanchez	Edinburgh
CaQTUS - (Calcium Quick Turnaround Universal System)	Industry	Project complete	Lucas	Oxford
Cryogenic qubit control interface using analog/ mixed-signal circuits and systems	Academic	Conclusion	Heidari	Glasgow
Quantum Computing for Modern Cryptography (QCMC)	Academic	Project complete	Wallden	Edinburgh
Transform-limited GHz-bandwidth control lasers for photonic simulators	Industry	Conclusion	Kolthammer	Imperial
RFSQ: Radio Frequency engineering for large scale Spin control in solid state Quantum systems	Academic	Conclusion	Balram	Bristol
Quantum Computing and Music	Industry	Conclusion	Miranda	Plymouth
Quantum mechanical simulation of the fabrication process of aluminium oxide tunnel junctions as superconducting qubits	Industry	Execution, Monitor & Report	Georgiev	Glasgow
Silicon qubit control with a 3D microwave cavity	Industry	Implementation	Fogarty / Fisher	UCL
Quantum compatible flip chip	Academic	Execution, Monitor & Report	Connelly	Imperial
MICRODOT: Microlens Integration for Compact & Robust Optical Delivery on Trap	Academic	Execution, Monitor & Report	Goodwin	Oxford

Project	PRF Category	Status	Lead Investigator	Lead Institution
Spin Qubits in Hexagonal Boron Nitride	Industry	Execution, Monitor & Report	Luxmoore	Exeter
Atomic quantum frequency conversion of on-demand photons	Industry	Implementation	Clark	Bristol
Quantum Amplification with Non-Linear Capacitance (QuANCap)	Academic	Execution, Monitor & Report	Warburton	UCL
Demonstrating analogue quantum computing approaches to optimisation using arrays of individually trapped neutral atoms	Academic	Execution, Monitor & Report	Pritchard	Strathclyde
Quantum machine learning for gravitational wave data analysis	Academic	Execution, Monitor & Report	Croke	Glasgow
Distributing big quantum computations over small quantum computers	Academic	Implementation	Heunen	Edinburgh
Robust quantum computation on superconducting qubits with fixed coupling	Industry	Implementation	Le Ginnosar	Surrey
Quantum Optimization for Logistics and Services (QOLS)	Industry	Implementation	Corne	Heriot-Watt
Coherent diamond microcavity system with group-IV colour centres	Industry	Execution, Monitor & Report	Gangloff	Oxford
Dielectric meta-surfaces for low-loss quantum photonic interconnects	Academic	Implementation	Patel	Imperial
Ion Trap Cavity Opto-Mechanics	Industry	Implementation	Goodwin	Oxford
ResQCCom (Responsible Quantum Computing Communication)	Industry	Implementation	Jirotka	Oxford

How to get involved

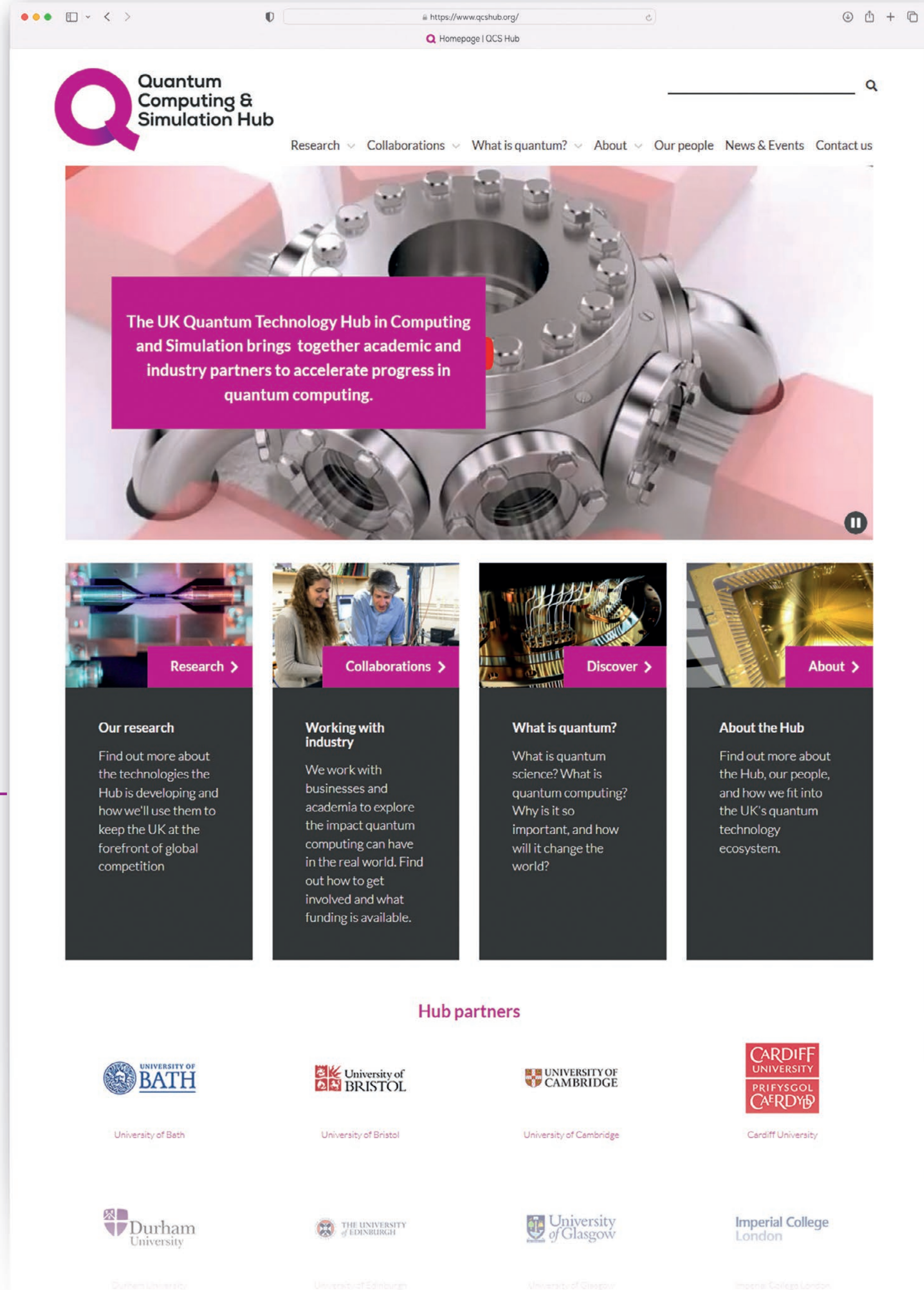
Get involved and find out more

In addition to our research, the Hub is here as a nexus for national and international stakeholders to learn about quantum computing & simulation, discuss the latest developments in the field and accelerate developments in the UK's quantum industry. We are keen to engage with a diverse range of individuals and organisations, and welcome all stakeholders, from technology providers to system builders, and software developers to end users as we accelerate our research, drive spinout companies and invest in our community.

With expertise and resources available to facilitate engagement and collaboration, we are keen to hear from entrepreneurs, investors and established technology companies looking for partnership or collaboration opportunities.

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

If you or your company have an interest in quantum computing and simulation and/or any of the above please get in touch via **engage@qcshub.org**



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