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Global Expert Mission
Quantum Technologies in the USA
2019

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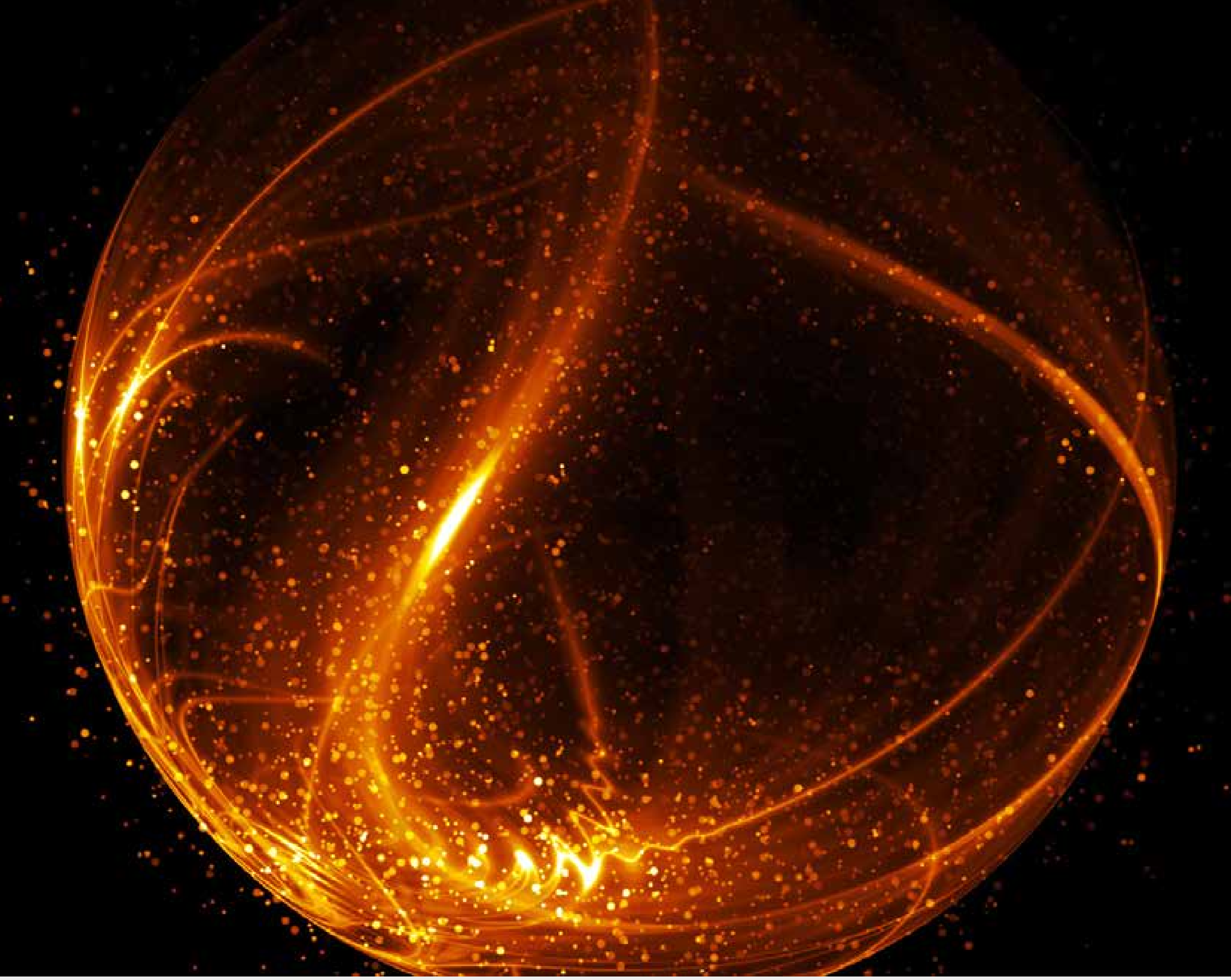

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Welcome

Innovate UK[1] launched its Global Expert Missions in October 2017, to help UK businesses become truly global enterprises through strategic collaboration. Delivered by the Knowledge Transfer Network (KTN)[2], the missions provide an expert-led evidence base to strengthen Innovate UK's global investment strategy: how and where it should invest to create UK business opportunities in partnerships with key economies.

In November 2019, an Expert Mission travelled to Washington DC, Colorado and California, following on from a smaller group who visited the Boston area in September. These missions sought to inform the UK's international strategy for quantum technologies by exploring the US quantum landscape and examining opportunities to collaborate with US organisations. This report summarises the information and insights gathered during the delegation's time in the US.

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[1] www.gov.uk/government/organisations/innovate-uk

[2] www.ktn-uk.org

1. Executive Summary

A new technological revolution is exploiting the quantum behaviour of matter. Practical quantum devices including sensors and clocks are already in the market, and within ten years a range of quantum technologies could be commercialised on a large scale, with potentially great benefits for society and the economy.

The UK National Quantum Technology Programme (UKNQTP) brings together academia, industry and government in a coordinated drive towards commercial applications[3], across quantum sensing, imaging, communications and computing. Now entering its second five-year phase, with committed and planned investment amounting to £1 billion, the programme has been a great success. But to reap the rewards, the UK must also forge links with the right international partners: not only universities and research organisations, but also global companies which can provide access to markets and finance.

Unsurprisingly, the USA is exceptionally strong in quantum science and technology. It leads the world in quantum computing, which could have the most profound impact of all quantum technologies: both as a threat to secure data transmission and as a tool that can solve many problems impossible for conventional computers.

A practical quantum computer remains several years off, but US business investment in this field is accelerating. Well-funded start-ups Rigetti Computing and PsiQ are joining the giants of Google, IBM and Honeywell at the front of the race to build the first effective machine. Other tech companies, including Lockheed Martin and federal agencies such as NASA, are exploring the possible applications of quantum computing.

Now the US government has stepped in with the National Quantum Initiative (NQI), a five-year, $1.27 billion programme. This will include up to ten new centres for quantum information science (QIS) research and education; and a business consortium, QED-C, has been set up to give a voice to the industry.

The initiative has a stated “science first” aim, with the expectation that the market will handle innovation – exploiting new science coming out of the federal programme. However, US government can also drive quantum technology directly through strategic procurement in defence and elsewhere.

The scale of investment and the quality of research are both impressive. As NQI is spread across several agencies and many labs, it is not yet clear how well coordinated the initiative will be; however, there is a smooth flow of people, ideas and sometimes funding between academia, industry and national labs. Joint ventures between national labs and universities, such as JILA and JPL, are effective players in the quantum landscape.

By comparison with the enormous computing effort, there seems to be relatively little work on quantum communications, sensors and imaging; however, the mission concentrated on civil applications rather than defence, where there may be greater activity in these fields.

We found a widespread appetite to collaborate with the UK, especially on quantum software, components, materials, and training.

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[3] www.gov.uk/government/publications/quantum-technologies-blackett-review

2. Quantum Computing Primer

While classical computers deal in bits of information, quantum computers use qubits. A qubit can have values of 0 or 1, just like a bit; and it can also be both at the same time: partly 0 and partly 1, in varying proportions. This is known as a quantum superposition.

Two or more qubits can be put into an entangled state, meaning that each one is affected by what happens to all the others. As more qubits are added, their entangled state can adopt a huge number of states simultaneously. In principle, this complexity allows some calculations to be performed much more quickly than on any classical computer.

The snag is that quantum states are fragile, prone to being altered by any interaction with the environment. Experimental quantum computers try to reduce this troublesome noise by using physical qubits that are isolated from the environment. Even these qubits show errors after a fairly short time, but if noise can be reduced below a certain threshold, it is possible to detect and correct such errors, producing a fault-tolerant quantum computer. This process is hardware intensive – you need about 1,000 physical qubits to encode the state of each error-corrected logical qubit. The known algorithms for this kind of computer need upwards of 1,000 logical qubits to be useful, so a practical full-scale quantum computer would need roughly a million physical qubits.

Meanwhile some researchers are trying to find useful calculations that can be performed rapidly, before the quantum information degrades too far, on a machine with 50 or more qubits that could be built within the next couple of years. This is known as noisy intermediate-scale quantum computing, or NISQ.

Hardware

Many technologies are competing to reach this goal, with qubits encoded in different physical systems, including neutral atoms, semiconductors and defect sites in diamonds. The two most mature approaches are:

- Superconducting circuits. Each qubit is stored in the form of electric current circulating around a circuit (cooled down so it reaches a superconducting state, where there is no resistance to current flow). Experimental machines of this kind have high clock speed (meaning each logical operation is performed rapidly) and at present relatively large numbers of qubits, with both Google and IBM running 53-qubit chips.
- Ion traps. Each qubit is stored in the energy state of an electron orbiting an ion. This technology has the lowest error rates (or highest fidelities). So far it has only been possible to control relatively small numbers of ion qubits, but one plan is to network small, high-quality ion modules to make a larger machine.

In the NISQ regime, the next couple of years may reveal which of these two approaches performs better. Google, among others, are predicting a full fault-tolerant superconducting machine in about ten years (section 3.4.1). With an alternative approach using photon qubits, PsiQ suggest they will reach that stage in only about five years (section 3.4.5).

Benchmarks and Landmarks

The power of a quantum computer depends on the number of qubits, their fidelity, and the time taken per logical operation, as well as other factors including how interconnected the qubits are to one another. IBM combine these factors into a single measure they call quantum volume[4], although this is not a universally accepted benchmark.

There is still argument over how to judge when quantum beats classical. In 2019, Google claimed to have achieved "quantum supremacy"[5]. The term is usually taken to mean overwhelming dominance – as implied by John Preskill when he defined the term in 2012 as quantum systems performing tasks "surpassing what can be done in the classical world"[6]. The sense used by Google was rather more modest, that their processor takes about 200 seconds to sample one instance of a quantum circuit a million times, while a state-of-the-art classical supercomputer would take 10,000 years. IBM disputes this, putting the classical time at 2.5 days. The

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[4] https://arxiv.org/pdf/1811.12926.pdf

[5] https://www.nature.com/articles/s41586-019-1666-5

[6] https://arxiv.org/abs/1203.5813

alternative term “quantum advantage” is usually taken to mean several orders of magnitude speed advantage. Perhaps a more telling landmark will be “useful quantum advantage”, when it becomes commercially worthwhile to use a quantum computer rather than a classical one.

Software

In parallel to hardware development, many teams are working to identify calculations and applications suited to quantum computers. Two algorithms are well known: Grover’s algorithm for searching unstructured databases; and Shor’s algorithm for factorising large numbers, which makes quantum computers a potential threat to the RSA encryption schemes widely used in banking and other high-security communication.

In the NISQ regime, people are hoping to simulate chemical reactions and solve optimisation problems in logistics and engineering. For fault-tolerant computers, more algorithms have been developed for tasks including pattern matching and solving sets of equations[7], but the field is young and a lot more fundamental work is required.

To enable people to write and run quantum programmes, software tools and languages include IBM’s Qiskit framework, as well as Google’s CIRQ software framework for NISQ computers, which is open source and can be used on ion-based or neutral atom machines, as well as superconducting circuits. Microsoft has created their Quantum Development Kit, and several companies are planning to make their hardware available through Microsoft’s AZURE cloud computing platform.

The full software stack needed to animate a quantum computer includes error correction and operating systems, and applications may turn out to be machine-specific, unlike the portable apps on classical computers today.

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[7] https://www.nature.com/articles/npjqi201523

3. The US Quantum Landscape

As you would expect of a country that spends more than half a trillion dollars[8] per year on R&D (more than a quarter of the global total), the USA is strong in most fields of science and technology, and quantum is no exception.

Academic centres of excellence include MIT, Harvard, UCSB, Stanford and Colorado. The National Institute of Standards and Technology (NIST) plays a prominent role in developing international standards, notably for timing and quantum secure communications.

National labs such as Sandia and Lincoln Laboratory provide world-leading fabrication and other facilities for quantum tech, as well as pursuing fundamental research. These labs can underpin continuity in innovation, being custodians of capability with long-term funded research, with less reliance on PhD students, postdocs and revenue generation than labs in the UK. Long term employees can develop deep skills and sophisticated tools and techniques.

Industry is investing heavily in quantum computing. Big corporations including IBM, Google, Intel, Microsoft, Honeywell, and Boeing are involved alongside start-ups such as Rigetti Computing and IonQ. Venture capital is relatively well informed about quantum technology. Other technology giants are involved in the quantum landscape, notably Northrup-Grumman, Lockheed Martin and Raytheon. However, much of their interest is related to security and defence, so falls outside the scope of this mission and report.

The government's new National Quantum Initiative promises to boost quantum information science to the tune of $1.27 billion over the next five years, with several new quantum centres being set up.

3.1 Government

This report covers agencies we met with, plus NIST. Other federal agencies with an interest in quantum technology, but not covered here, include:

Department of Agriculture (USDA)
National Institutes of Health (NIH)
Department of the Interior (DOI)
Department of Homeland Security (DHS)
Department of State (State)
Department of Transportation (DoT)
National Security Agency (NSA)
Office of the Director of National Intelligence (ODNI)
Office of Management and Budget (OMB)

3.1.1 National Quantum Initiative

"We see government's role as to make certain we are understanding what the scientific opportunities are, while companies look at market opportunities." Jake Taylor, Assistant Director for Quantum Information Science, White House Office of Science and Technology Policy

The National Quantum Initiative Act was signed into law in December 2018. It aims to forge a systematic national approach to quantum information research and development. Its key policy provisions are to:

- choose a science-first approach
- create a quantum-smart workforce
- deepen engagement with quantum industry
- provide key infrastructure
- maintain national security and economic growth
- advance international cooperation.

The act creates a multi-agency programme spanning the National Institute of Standards and Technology (NIST), National Science Foundation (NSF) and Department of Energy (DOE). These three agencies will support R&D and education in quantum information science (QIS), and facilitate partnerships between national labs, academia and business.

The act authorises a total spend of up to $1.27 billion over five years. This figure is neither a cap nor a floor, only a guideline; each year, the money must be appropriated by an agreement in congress. One of the main provisions is funding for new national QIS research centres, which will be competitively

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[8] https://www.nsf.gov/statistics/2019/nsf19308/

awarded. NSF will set up two-to-five centres, funded at up to $10 million per year; DOE gets the same number of centres but more funding, up to $25 million per year each.

Coordination

Three groups will coordinate and administer the initiative:

- The Subcommittee on Quantum Information Science (SCQIS) of the National Science and Technology Council coordinates R&D programmes and budgets across federal agencies, assesses infrastructure and workforce requirements, and establishes goals and priorities. In September 2018 they released a national strategic overview[9] of quantum technology.

  The subcommittee must have representatives from NIST, NSF, DOE, NASA, the Department of Defense, Office of the Director of National Intelligence, White House Office of Management and Budget, and White House Office of Science and Technology Policy, and any other agency or department the president considers appropriate.

- The National Quantum Coordination Office (NQCO), within the White House Office of Science and Technology Policy (OSTP), will serve as a point of contact for NQI. It will also support basic quantum science, promote commercialisation of federal research, and conduct outreach.
- The National Quantum Initiative Advisory Committee, established in August 2019, has representatives from industry, universities, and federal laboratories. It will give advice on R&D, standards, education, tech transfer, commercial applications and national security issues. The committee will meet at least twice a year to advise OSTP.

Quantum Categories

The Subcommittee on Quantum Information Science divides quantum science and technology into seven areas:

S1. Quantum sensing: leveraging quantum mechanics to enhance the fundamental accuracy of measurements and/or enabling new regimes or modalities for sensors and measurement science. (DOD, DOE, DHS, DOI, NIST, NSF, ODNI)

S2. Quantum computing: from devices and algorithms for analogue simulation of quantum systems in the laboratory to controlled digital quantum computers. (DOD, DOE, NASA, NIST, NSF, NSA, ODNI)

S3. Quantum networking: exploring and using coherent or entangled multi-party quantum states, distributed at distances, for new information technology applications and fundamental science. (DOD, NASA, NIST, NSF)

S4. Scientific advances enabled by quantum devices and theory advances: improved understanding of materials, chemistry, cosmology, classical computation techniques, and other aspects of fundamental science. (DOE, NIST, NSF)

T1. Supporting technology: necessary analogue, digital, electrical, mechanical, optical, computational, and cryogenic systems and techniques that underpin the fundamental science areas. (DOD, NASA, NIST, NSF, NSA, ODNI)

T2. Future applications: opportunities for improvements in operations research, optimization, machine learning, drug discovery, etc. (All SCQIS agencies)

T3. Risk mitigation: necessary infrastructure and support for quantum technologies and their impact, such as quantum-resistant cryptosystems and other post-quantum applications. (DHS, NIST, NSA)

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[9] https://www.whitehouse.gov/wp-content/uploads/2018/09/National-Strategic-Overview-for-Quantum-Information-Science.pdf

Science First

The stated "science first" direction appears to be very different from the UK programme's emphasis on technology. Rather than being a technology transfer programme, the NQI is aimed at providing a critical mass to solve big interdisciplinary science challenges, so that industry can then exploit these discoveries.

According to the OSTP, three main areas of quantum technology have three distinct drivers:

- Quantum sensing – driven by market-requirements.
- Quantum computing – driven by large private investors.
- Quantum networking – the long-term work enabled by NQI.

However, the NQI is not the only source of government money. Procurement and SBIR (see box below) drive growth in early-stage technology.

Innovation Funding

While fundamental research has bipartisan support, applied research funding is less favoured by political conservatives, on the grounds that the federal government should not pick winners and losers in the marketplace, or pay for work that the private sector should be investing in anyway. However, several mechanisms channel government money into business innovation. US government procurement covers 100% of the costs to develop new technologies, plus a 10% profit margin. The Small Business Innovative Research (SBIR) programme[10] gives grants to small businesses (up to 500 employees) for R&D with the potential for commercialisation. Every federal agency with an R&D budget of $100 million or more is required to put 3.2% of it into SBIR. There are also federal programmes that fund high-risk research projects across business, universities and government labs; including DARPA (Defense Advanced Research Projects Agency) whose main customer is the Department of Defense; and ARPA-E (Advanced Research Projects Agency-Energy) which is more business-facing.

3.1.2 NIST

The National Institute of Standards and Technology[11] is a national laboratory and a government agency with a mission to "promote US innovation and industrial competitiveness by advancing measurement science, standards and technology".

NIST operates the Joint Quantum Institute and a Joint Center for Quantum Information and Computer Science with the University of Maryland. It supports JILA, a joint centre at the University of Colorado Boulder (page 13).

NIST is instructed to spend up to $80 million per year on NQI activities over the next five years. Part of this is to help establish measurement and standards infrastructure necessary for commercial development of quantum applications. As directed by the act, NIST has created a quantum industry consortium (page 14).

As with other US national labs, NIST is a valuable resource to the quantum community, offering infrastructure and highly-trained staff scientists with the longevity to pull technologies through.

3.1.3 National Science Foundation

NSF funds all fields of fundamental science and engineering. Its 2019 budget of $8.1 billion is comparable to that of UK Research and Innovation, and relatively small compared with DOE and DOD.

NSF already funds QIS research and education through several of its divisions, and in 2016 identified the "Quantum Leap"[12] as one of its ten Big Ideas. This will be a set of activities "enabling a community of researchers from different disciplines to come together to conduct truly convergent, innovative research". The programme covers fundamental quantum science as well as quantum technologies.

In September 2019, NSF announced $31 million in awards through new interdisciplinary QIS grant programmes, bringing together physicists, engineers and computer scientists; and it is considering proposals for foundries to develop quantum materials and devices.

Challenge Institutes

Within NQI, NSF's job is to support research and training. Specifically, the act directs the agency to establish between two and five "multidisciplinary centers for quantum research and education." Each will receive up to $10 million per year; although NSF's current budget plan is to spend up to $5 million per centre. These will be known as Quantum Leap Challenge Institutes.

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[10] https://www.sbir.gov/about/about-sbir

[11] https://www.nist.gov/

[12] https://www.nsf.gov/news/special_reports/big_ideas/quantum.jsp

Applicants can include higher-education institutions and non-profit organisations, as well as multi-institutional collaborations that can include private-sector bodies. In October 2019 NSF selected 13 university consortia to receive $150K to further their conceptualisation bids. Department of Energy representatives will observe the NSF panel that reviews the full proposals.

Some Challenge Institutes are likely to be motivated by particular scientific or technological problems, such as the need for a quantum repeater to enable quantum networking.

3.1.4 Department of Energy

DOE's Office of Science is a huge research organisation covering a very wide range of fundamental and applied sciences from advanced computing to genetics. With a $7 billion budget it runs 17 national laboratories. DOE has ramped up its quantum investment to $120 million in fiscal year 2019, and the 2020 US budget allocates $195 million.

National Research Centres

The National Quantum Initiative directs DOE to establish between two and five national QIS research centres; each is to be allocated up to $25 million per year. Like the NSF centres, these awards will be for five years with the possibility of renewal. Applicants can include national laboratories, universities, research centres, multi-institutional collaborations and "any other entity that the Secretary of Energy determines to be appropriate." In 2019 DOE put out a request for information soliciting ideas for centres, and plans to issue a funding opportunity announcement in 2020. DOE must also provide research experience and training for students in quantum information theory, quantum physics, quantum computational science, applied mathematics and algorithm development, quantum networking, quantum sensing and detection, and materials science and engineering.

DOE delegates on the mission represented four of the six departments of DOE's Office of Science:

Basic Energy Science is investing in 58 projects, covering technologies supporting QIS (including materials for next-generation devices) and applications of quantum sensors and computers.

Advanced Scientific Computing Research has invested a total of $130 million in QIS, including two quantum computing hardware testbeds, based on ions (at Sandia Laboratory) and superconducting qubits (at Lawrence Livermore National Laboratory), which are intended to explore ideas not ready for industry to adopt, such as alternative chip architectures. There are also theory programmes on: performance assessment for quantum computing (how hardware characteristics are related to what you can do with that machine); quantum networking (looking ahead at how a quantum internet might work); and abstract algorithm development.

High Energy Physics is funding quantum sensors and superconducting RF cavities to detect dark matter and other new particles, and using QIS to investigate questions in particle and fundamental physics, such as parallels between entanglement in quantum technology and the physics of black holes, wormholes and the nature of space-time.

Nuclear Physics is investigating quantum algorithms for simulating nuclear physics; the effects of environmental radiation on qubits; and quantum sensors that could work in the high magnetic fields of nuclear physics experiments.

Opportunities

UK delegates noted the large scale of quantum activities across DOE.

For collaboration with some of DOE's more fundamental science projects, the best UK link is likely to be the new Quantum Technologies for Fundamental Physics programme[13].

Advanced Scientific Computing Research said that they would like to find a way to connect with similar quantum computing efforts in other friendly countries, both hardware and software. DOE will be opening their hardware platforms at the Lawrence Livermore National Laboratory and at Sandia Laboratory for external users to help develop the technology, which could be something for the UK to engage in.

3.1.5 DOD and Lincoln Laboratory

The Department of Defence (DOD) is not involved in the National Quantum Initiative, but has been working to develop and exploit quantum technologies since the 1990s. In the near term they are especially interested in clocks, gyroscopes, and sensors for gravity and magnetic and electric fields. DOD has no openly published formal position on quantum key distribution (QKD).

They also have some interest in the applications of quantum computing – for example, the navy spends more than $1 billion a year dealing with corrosion, and quantum simulators might eventually lead to better coatings or alloys – but suggest that it will be at least ten years before quantum computing becomes significant, and that more algorithm development is needed to drive the field.

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[13] https://stfc.ukri.org/funding/research-grants/funding-opportunities/quantum-technologies-for-fundamental-physics/

DOD's advanced research projects agency, DARPA, has an excellent track record of innovation. DARPA programmes have led to the creation of some of the main commercial quantum technology companies in the USA, including AOSense and Cold Quanta (page 17). It was suggested that one reason for this success is an appetite for failure. Despite being rigorous in their initial choice of programmes, only 10% succeed, because DARPA tries to push investigators to be ambitious.

Opportunities
DOD were positive about UK work including gravity sensing and chip scale atomic clocks. They suggest that the big opportunity is to invest in better understanding use cases of sensors and clocks, to find out where the biggest returns will be.

Lincoln Laboratory
The MIT Lincoln Laboratory in Lexington, Massachusetts, is a DOD-funded centre that develops advanced technology for national security needs. They are world leaders in fabricating niobium films for superconducting circuits. The lab is also working on trapped-ion qubits, quantum sensors, clocks and communications.

The lab's magnetic sensors based on nitrogen-vacancy diamond (NVD) are aimed at navigation and medical applications (high-resolution microscopy). These have already had some field deployment. They have also developed ion-based sensors and clocks, and are looking at the integrated electronics required to get equipment out of the lab.

Lincoln Laboratory are very open to having discussions about possible use cases for quantum sensors, which might be a fruitful avenue to identify areas for collaboration. Despite issues over DOD funding and intellectual property, they saw no substantive barriers to collaboration with UK players, even on more security-sensitive areas, as long as the right agreements and permissions are in place. The UK could also make use of its fabrication capabilities.

3.1.6 Air Force Research Laboratory

AFRL is conducting research into free-space optical links; ruggedizing clocks and other technologies; quantum radar; and key supporting technologies including specialist lasers and materials.

Their Rome lab in New York State is setting up an Innovation Centre just outside its gates that will include QIS. AFRL is also an IBM Q Network Hub, giving it access to IBM's quantum computing systems to explore practical applications.

AFRL is already engaged with UK research groups. They have an office in London that works with UK researchers and mentioned being keen to collaborate on specialist laser sources for clocks and other quantum technology.

While they do not fund QKD specifically, they do work on fundamental aspects of quantum communications, including distributed entanglement. For example, using adaptive optics for ground-to-satellite daytime quantum communication.

Along with the Army Research Laboratory and the Office for Naval Research, AFRL runs the Multidisciplinary University Research Initiative (MURI) programme, to support research intersecting more than one traditional discipline. Awards are for three to five years, at up to $1 million per year.

3.1.7 NASA

NASA's AMES Research Center in California has two main interests in quantum technology:

Exploring the near-term uses of quantum computing. They are not building hardware, so are looking for opportunities to use small quantum processors to test algorithms – especially hybrid quantum-classical machines, where they believe the early gains will come. They are keen to collaborate with academic groups on algorithm development, especially for optimisation problems including logistics, and advanced materials simulation. The group is also simulating superconducting hardware to better understand causes of noise.

Sensors, communications and networking for space missions. One target is investigating quantum technology for secure communication between spacecraft and other assets. They also suggest that quantum magnetometers and other sensors may be ready to fly on interplanetary missions within five to seven years, perhaps in time for the planned 2026 mission to Titan.

3.2 Academia

3.2.1 Harvard

Harvard hosts two new quantum technology endeavours:

- The Max Planck Harvard Research Center for Quantum Optics, a collaboration between Harvard's physics department and the Max Planck Institute of Quantum Optics (MPQ) in Munich – both of them leading research centres in quantum science.
- The Harvard Quantum Initiative in Science and Engineering (HQI), a community of researchers aiming to transform quantum theory into useful systems and devices. This programme is preparing Harvard for NQI funding. Their

annual budget is $3 million. The initiative is mainly funding Post Doctorial Research Associates for now, but it will soon establish a new graduate programme and external collaboration programme, coordinating with MIT, state and local government, and industry. A new quantum engineering programme across computing science, engineering and physics is recruiting ten faculty positions.

Harvard's technological focus is on computing, simulation and quantum optics, with notable work on quantum repeaters and programmable simulators using Rydberg atoms.

They spoke of the opportunity for relationships between universities, national labs, start-ups and big industry and saw value in the UK NQTP's integrated approach.

3.2.2 MIT

MIT's Center for Theoretical Physics has a large group working on quantum information and computing, notably in algorithms, complexity, measurement and control.

MIT discussed how valuable it is for students and early career researchers to spend time in industry. They use summer internships extensively, which they consider to be very valuable. However, they also say that industry in the US is creating a talent vacuum, making it difficult to hire into academia.

They are open to collaboration, favouring a model of exchange fellowships (such as the Marie Curie Fellowship). There is considerable enthusiasm for the concept of the UK National Quantum Computing Centre, which they see as a potentially valuable focus for collaboration.

3.2.3 Yale

Yale has long been at the forefront of quantum research. Superconducting technology developed at Yale[14] has been adopted and adapted by many others, including IBM and Google, and the university has trained many of the people working on superconducting quantum computing around the globe. In February 2019, Yale researchers announced a breakthrough in quantum computing when they developed a universal entangler.

The Yale Quantum Institute was founded in 2014 and brings together around 150 physicists, engineers, computer scientists, materials scientists, chemists, biologists and other researchers to study quantum information, computation, measurement and sensing. It has had $50 million federal funding to date ($6 million per year) and has world-class facilities, including 12 dilution fridges. The institute is a world leader in quantum hardware, photonics, phononics and the theory of bosonic quantum information. The university has spun-out Quantum Circuits Inc[15], a company aiming to "develop, manufacture, and sell the first practical quantum computers".

Yale researchers are pursuing high-fidelity error-corrected qubits, and are not interested in NISQ (noisy intermediate-scale quantum computing – see section 2). They are acutely aware of the risks of overselling quantum computing and insist that fundamental science barriers mean that some applications may not be possible. So they are still focused on that fundamental science. Nevertheless, they have industry ties with IBM, Raytheon, Microsoft and Google.

Collaboration may be possible on topics that directly align with the university's established research agenda.

3.2.4 JILA

JILA is a joint institute of the University of Colorado and NIST. Its research includes fundamental aspects of quantum measurement and technology, matter-light interaction, and precision laser design.

JILA has submitted a multi-university proposal to NSF for a Quantum Leap Challenge Institute. In January 2019, NIST and the University of Colorado, along with local companies including Lockheed Martin and Honeywell, founded the CUbit initiative[16]: an interdisciplinary hub that aims to build a foundation for applying and commercialising novel quantum technologies.

With a gift from Google, JILA is setting up the Boulder Cryogenic Quantum Testbed: a non-profit, pre-competitive research facility for developing and disseminating standard protocols to measure the quality and performance of the resonators used in quantum computing circuits.

Opportunities

UK delegates were impressed by the research at JILA, with highlights including research into atomic clocks and degenerate gases. For example, they are investigating ways to get directional information from a vapour cell magnetometer, which would make a powerful platform for navigation and other applications.

There is strong collaboration between theory, optics and sensing; and close integration between NIST and the university – with integrated programmes, students and faculty. JILA is also vertically integrated, maintaining machine, electronics and other supporting workshops; giving students access to everything needed to do original research. Secure funding from NIST enables academics to take on big, long-

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[14] https://www.nature.com/articles/nature08121

[15] https://www.quantumcircuits.com

[16] https://www.colorado.edu/initiative/cubit/

term challenges with five-to-ten-year horizons, whereas more common two-to-three-year grant cycles encourage lower-risk research.

Local entrepreneurial culture seems to be supportive and successful in taking research out of the lab. JILA has links to the university's school of business, and encourage spin-outs. They are keen to work with the UK community.

3.2.5 Caltech

Based in Pasadena, the California Institute of Technology (Caltech) is a small university with only 320 faculty members but an outstanding record in scientific research. A strong portfolio of quantum theory and experiment is spread across three of the six faculties, brought together under the Institute for Quantum Information and Matter (IQIM), an NSF Physics Frontiers Center. It has active partnerships with Jet Propulsion Labs (JPL), NIST and the University of Calgary.

A long-term, stable programme of fundamental research is focusing on the hard questions that could be transformative for quantum technology, including sensors, clocks and computers. Key areas are quantum information, dynamics, many-body entanglement, quantum limits of mechanical systems, quantum phases of matter and topological physics – where the goal is a stable self-correcting quantum memory.

In 2017, along with national laboratories and industry partners including AT&T, Caltech helped to found the Alliance for Quantum Technologies[17] (AQT), a consortium aiming to accelerate progress in QIS, notably in quantum networks and communication, and quantum machine learning.

IQIM's active outreach programme[18] has produced a film about quantum technology featuring Paul Rudd, Stephen Hawking and Keanu Reeves, and helped to develop a module for Minecraft to bring quantum concepts into the game.

3.2.6 Stanford

Stanford's high-quality quantum science programme is especially strong on imaging and novel techniques to investigate materials and devices. Some of their fundamental research is already transferring into technology that can be commercialised.

Work includes:

- A multipass transmission electron microscope, which bounces electrons back and forth through a sample. This can image delicate samples, such as DNA, without damaging them. A commercial system is under construction with Electron Optica, Delong and Kimball Physics.
- Entangled atomic ensembles for atomic clocks, beating the standard quantum limit.
- Multi-label fluorescence lifetime imaging microscopy, single-molecule lifetime spectroscopy, and fast single-frame fluorescence lifetime imaging microscopy with 10^3–10^5 times higher throughput than single-photon counting.
- Atom interferometers searching for dark matter, at Fermilab's MAGIS-100 experiment.
- The SQCRAMscope, a quantum sensor that uses an ultracold quantum gas as a micron-resolution magnetometer. It can image DC electron transport and magnetization in room-temperature and cryogenically-cooled quantum materials with unprecedented sensitivity.
- A single-electron transistor on the tip of a scanning microscope to measure local potential, charge distribution, and electronic compressibility of 2D materials. This can be combined with a SQUID for simultaneous magnetic field measurement, and could be used to investigate noise on the surface of superconducting materials and paramagnetic defects. NPL has developed a complementary technique called nearfield scanning microwave microscopy.

UK companies such as M Squared Lasers, Covesion and Element Six are key suppliers to Stanford's experimentalists, and they praised the UK ecosystem that has allowed these companies to flourish. Is there an opportunity for UK companies to grow this market further?

3.3 QED-C Industry Consortium

NIST has set up an industry consortium to provide a collective industry voice and help guide quantum technology development in the USA. The Quantum Economic Development Consortium (QED-C) includes more than 80 corporations, 16 academic institutions and 7 professional societies/NGOs (see Annex 3).

Its aims are to:

- identify gaps in enabling technology and infrastructure, and help to fill those gaps
- foster sharing of intellectual property and efficient supply chains
- determine workforce needs
- provide efficient public-private sector coordination
- support standards development for the emerging quantum industry
- highlight best use cases
- produce roadmaps
- help agree functional specifications for vendors.

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[17] http://inqnet.caltech.edu/index.html

[18] https://iqim.caltech.edu/outreach/

Activities will cover technology readiness levels 3-5, covering the development of prototypes, common enabling devices, components and subsystems.

QED-C is initially funded by NIST, but aims to be self-funding. Annual membership fees will cover operations and internal research such as surveys. They are set at $200K for large companies; $100K for medium; $25K for small companies; and $1K for start-ups.

Starting in 2021, QED-C will arrange R&D to close gaps in infrastructure and enabling technology. Funding for this will be 50% from the private corporations concerned and 50% from NIST.

Opportunities

The reactions of UK representatives were mainly positive. The list of companies involved is impressive; the aspiration is good. Initial work on road-mapping, use cases and agreeing requirements is likely to be very beneficial.

There are clear mutual interests with the UK programme in understanding future workforce needs, developing clear use cases and creating roadmaps, and it would be useful to explore how they could engage in the UK programme given the majority of members have global activities.

QED-C are keen to partner with countries that have shared values. They hope to open the consortium to tier 2 members ("friendly non-US entities") around March 2020. They also want to set up a chapter in Europe, and there was a strong sentiment that the UK should be involved.

3.4 Business

Several IT and defence majors are making large investments in quantum technology, and some very well-funded start-ups are rivalling their work. The investments by IBM, Google, Intel and Microsoft are high profile; Lockheed Martin, Northrup Grumman, Honeywell and others are moving to more public programmes; others remain commercially confidential.

Quantum computing dominates this commercial landscape, with a total investment of several hundred million dollars per year. Google, IBM and Rigetti Computing are leading in superconducting circuit machines; Honeywell and IonQ in the ion-based approach. Two big players are pursuing less established technologies: Microsoft with topological qubits, and PsiQ with qubits made from light.

Other fields of quantum technology are less well represented, but standouts include ColdQuanta, whose cold-atom technology goes into information processing, gravimetry, magnetometry, timekeeping and navigation; and AOSense, which makes cold-atom sensors.

The US also benefits from relatively quantum-savvy venture capitalists and the critical mass of Silicon Valley.

3.4.1 Google

A leading player in superconducting quantum computing, with hardware development in Santa Barbara and the theory team in Venice, Los Angeles, Google made the news in 2019 with their announcement of the first demonstration of "quantum supremacy" using their 53-qubit Sycamore chip (see section 2).

Google say that they see the pathway to quantum computing as a global collaborative endeavour, and plan to publish details of their hardware and systems, and give collaborators direct access to their hardware and support.

Hardware

One challenge is material imperfections leading to errors. Google is working closely with NIST and the University of Colorado Boulder to establish a testbed to address such challenges for superconducting quantum computers. Other hardware challenges include miniaturising wiring, interconnects and microwave components.

Algorithms and Applications

We visited the software and theory group in LA and noted that several senior members of this team are UK-trained.

The theory group is now looking for NISQ problems they can tackle with existing hardware, in fields such as quantum simulation and machine learning. They are funding academic groups to develop algorithms, including one in Oxford. (In all, they fund 30 research groups in 8 countries, although that includes hardware as well as algorithms and applications.) Google will have priority access to developed software, and this process will also spread use of their CIRQ platform.

Working with the UK

Through an EPSRC Prosperity Partnership scheme[19], Google is collaborating with University College London (UCL), the University of Bristol, and UK start-ups GTN and Phasecraft, on simulation, prototyping, verification and benchmarking.

3.4.2 Rigetti Computing

"For first stage investment there is no better place than Silicon Valley."
Chad Rigetti, founder and CEO, Rigetti Computing

Based in Berkeley, California, Rigetti Computing is among the leaders in superconducting circuit technology. They are a full-stack quantum computing company, meaning that they design and fabricate chips, integrate them, and write

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[19] https://www.ucl.ac.uk/news/2018/sep/ucl-partners-google-grow-quantum-software-industry-uk

controlling software. Like Google they are plotting a path towards a full fault-tolerant machine, via NISQ capability.

Founded in 2013 by Chad Rigetti, the company was initially funded privately, until it subsequently found an angel investor who still sits on the board. This year they applied for SBIR for the first time.

Having doubled in size over the past year, Rigetti Computing now has 150 employees, with sites in Berkeley, Washington, Adelaide and London. They built a fabrication facility in Fremont, about 30 miles south of Berkeley, so that they could control chip manufacture directly. The facility also sells services outside of Rigetti Computing.

The firm say that they are always thinking on a five-year timeframe, and aiming to strike a balance between long-term capability building and near-term demonstrations, which helps VC engagement but can hinder technical progress.

Their technology is a combination of tuneable qubits (like Google) and fixed frequency qubits (like IBM). They have developed high-density integrated microwave components. A critical element of each qubit is a superconducting component known as a Josephson junction, and these pose several fabrication challenges, such as the need for precise control of the oxide layer thickness. Performance is assured by calibration, metrology and modelling, and they can predict qubit frequency by room-temperature resistance testing.

Rigetti Computing say that quantum computing is a pace-of-innovation game rather than a volume game, which is why the traditional chip manufacturers are unlikely to get involved. They anticipate that quantum pioneers will dominate for a while, but then big corporations will jump in and provide cloud services. Rigetti Computing are also focused on cloud-based computing, and their customers already include government agencies and commercial companies. User pull is coming from people who now use classical high-power computing.

Rigetti Computing opened their London office because of the UK's strength in software companies, and they are particularly interested in collaborating on algorithms and noise reduction in hardware.

3.4.3 Honeywell

Honeywell is a consumer and engineering conglomerate. Before their move into quantum technology, Honeywell already had expertise in ultra-high vacuum, lasers and optics, cryogenics, complex controls, microfabrication and magnetics.

Honeywell Quantum Solutions[20] has more than 100 scientists and engineers, mostly in Colorado, some in Minneapolis. Having operated since about 2013, they went public in October 2018.

They are making ion-based devices on linear trap and grid architectures. The ions are shuttled around, and entangled by putting two in the same well. This technology gives very high-fidelity qubits. These qubits are also fully connected; that is, any one can talk to any other. The qubits are optical (addressed with lasers).

The near-term target is "classical impractical" – achieving a calculation that would be possible but not practical for a classical computer.

Opportunities
UK representatives were impressed with the team, the massive scale and funding level on display in the lab, and the corporate vision.

3.4.4 IonQ

"Industry involvement and risk-taking investors are critical to the ecosystem."
Chris Monroe, Co-founder & Chief Scientist, IonQ

Based in College Park, Maryland, IonQ is developing a general-purpose trapped-ion quantum computer, and software to go with it.

IonQ is working simultaneously on three generations of quantum computers, with separate teams. Their attitude is that while other approaches still require fundamental physics research and development, the ion trapping approach is further along, so is able to focus on engineering the rest of the stack.

Eventually they foresee a worldwide multinational approach, and plan to bring together a consortium to build the next-generation machine, requiring billions of dollars of investment.

Much of the application software will probably be developed by big quantum companies (Microsoft, Google, IBM). At the same time, university computer science researchers will be needed to span the layers between high-level algorithms and operating-system level.

When they started, experts made any tweaks or changes to calibration, but at this stage they have created systems to automatically recalibrate, so a supply of PhD-level talent is not a problem.

3.4.5 PsiQ

"There may be a million ways to make a qubit but there is only one way to make a million qubits."
Stu Aaron, PsiQ Chief Operating Officer

This start-up in Palo Alto, close to Stanford University, is taking a radically different approach to quantum computing. While most of the big players use either superconducting

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[20] https://www.honeywell.com/en-us/company/quantum

circuits or ions, PsiQ encodes their qubits onto photons. They believe that this can achieve the scale required for fault-tolerant computing much sooner than the other approaches, because it exploits the power of conventional silicon manufacturing. It would also be fully compatible with quantum communications.

Quantum states of photons are protected due to their extremely weak interactions, but the same quality makes it difficult to implement logic gates. PsiQ uses a process called measurement-induced nonlinearities[21]. Since photons travel at the speed of light, timing their arrival to particular circuit elements is critical, but PsiQ claims to have solved this with a design that means each photon travels exactly the same distance.

A high-volume CMOS foundry is making silicon optics for them on a 300mm wafer. Millions of chips are then tested using automated equipment. The aim is to gradually improve the fidelity of these chips until they pass the fault-tolerant threshold.

Like other QC pioneers the business model is cloud computing, but, unlike most, PsiQ is not interested in NISQ systems, focusing instead on building a fault-tolerant machine within five years, well ahead of Google's 10-year estimate.

They have also developed a 40-qubit simulator of a photonic computer, which has already attracted paying customers.

3.4.6 ColdQuanta

ColdQuanta is based in Boulder, Colorado, with an office in Oxford, UK. It sells cold-atom and ion systems based on research performed at JILA (page 13), which are used in a wide range of quantum tech applications including navigation, communications and computing. Main markets include the scientific community and defence. The International Space Station's Cold Atom Lab uses their technology.

Their establishment and growth were heavily reliant on SBIR funding and government contracts. Government contracts will pay the full costs of a project, including 100% capital, plus profit. For ColdQuanta, the upshot is that the US part of their business became profitable within three years, but the UK part will take much longer.

3.4.7 QuSpin

A small company with 13 employees, QuSpin leads the field in vapour-cell quantum magnetic field sensors, which are highly sensitive and work at room temperature.

The company's CEO was formerly at NIST where he worked on miniature clocks, and realised the potential of the technology for very sensitive magnetometry based on sensors not requiring cryogenic cooling. QuSpin was established through a series of SBIR contracts totalling more than $12 million.

The main market is medical applications, in particular, a brain imaging technique known as magnetoencephalography (MEG). QuSpin supplies sensors to a world-leading MEG project based at Nottingham. While the UK would benefit from its own capability to manufacture these sensors, the relationship with QuSpin has been highly successful, and there is scope for additional collaboration with UK companies and hospitals.

The company is also working on a foetal heart monitor, and on defence applications including a DARPA-commissioned magnetic sensor for unshielded environments.

3.4.8 Lockheed Martin

Lockheed Martin is a large security and aerospace firm specialising in advanced technology, with its headquarters in North Bethesda, Maryland. They have a broad interest in quantum applications, including quantum simulation to design new alloys, and sensors such as DARK ICE (diamond magnetometry for GPS-denied navigation).

The quantum team has early experience in quantum computing, with their own quantum annealer from D-Wave. They spoke with some passion on the benefits of playing with this machine, driving new ideas into conventional computer science for problems including scheduling and flight control; and they are open to giving third party access to it.

The company is open to pre-competitive stage collaboration. For example, they are exploring thermal annealing approaches in a new programme with Lincoln Laboratory and Northrop Grumman – recognising the benefits of leaving competition concerns for later.

3.4.9 Quantum Thought

Quantum Thought, a venture capital firm based in Silicon Valley, describes themselves as a "launchpad for the founding generation of quantum computing companies". They are looking for quantum intellectual property to spin out, and their first outing is QSecure, which sells quantum security – essentially a management layer tying together specific technical solutions.

They run events to bring in other investors, and expect their Quantum Fund to reach more than $50 million in early 2020, and $250 million in 2023.

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[21] https://www.nature.com/articles/35051009

4. Relative Strengths and Priorities

In basic terms, the US is about scale and pull, while the UK is coordination and push.

The US is clearly investing a huge amount of quantum cash, through government, venture capital and big corporations. US investors appear to be less risk-averse generally, whereas, in the UK, government investment is not matched by the private sector.

However, the US approach remains fragmented, which may mean that the huge investment is not being put to work efficiently. The UK's coordinated programme is still an advantage.

The "science first" policy of the US National Quantum Initiative aims to seed research that corporations can then pull out of the lab and into innovative commercial technologies. It will also drive technology directly by increasing research labs' demand for components. By contrast, the UK has a technology push programme, largely because there is still little UK industry or defence spending to pull technologies through. Opinion is divided on whether pull or push will be more effective.

Despite the apparent absence of collaborative industry R&D funding, the USA benefits from government contracting and the industry funding schemes SBIR and Small Business Technology Transfer (STTR). SBIR has kick-started new quantum companies with 100% funding of over $1 million, while government contracts to procure new technologies at 100% of full costs plus a profit element have enabled companies to grow and gain a toe-hold in the market, removing the risk for start-ups. Such generous funding is unavailable in the UK. Nevertheless, small quantum businesses in the UK are thriving, notably firms that supply quantum components and materials.

4.1 Technologies

The US leads the world in quantum computing hardware. The UK is recognised as a key player in quantum software, sensing, cryogenics and components.

4.1.1 Computing Hardware

The US is ahead of the UK overall, with projects working on larger and more powerful computers.

Academic groups including Yale, Berkeley and Chicago are well established in superconducting circuits ion traps, semiconductor qubits, neutral atoms and diamond NV centres. Research groups have been absorbed by large US tech companies, who are leading the hardware race from the perspective of number of qubits and quantum volume.

However, the UK is making fundamental advances in many areas, particularly in ion traps, photonics and spin qubits, which could pay off in the future as the technology matures. The UK's National Physical laboratory is a key player in research on noise and decoherence in superconductors. The UK's strength in ions parallels that in the US, although that may change with growing US activity, especially at IonQ and Honeywell.

4.1.2 Software

The software sector is thriving in both the US and UK, with a healthy mix of fundamental and applied research.

The UK is recognised as being strong in theory, algorithms and applications, with companies such as Riverlane and Rahko as well as excellent academic groups at Oxford (particularly in quantum computational chemistry), UCL (machine learning), and Bristol (fundamental algorithms), rivalling software research at MIT, IBM, Google, Microsoft and Zapata. This recognition means that US companies are aggressively hiring UK software and quantum chemistry experts.

4.1.3 Quantum Communication

The UK is making rapid progress in this technology, and also leads on the development of international standards. By contrast we saw relatively little evidence of quantum communications work in the USA, despite the NQI's stated ambition to enable quantum networking.

The message from most agencies and companies is that quantum key distribution is out of favour as a solution to secure communications – at least publicly. Instead, post-quantum cryptography (PQC) is the favoured solution. NASA and the DOE Office of Electricity are also both still interested in QKD; and there may be considerable undisclosed activity elsewhere.

4.1.4 Timing, Sensing and Imaging

In the USA these fields are all classed under "sensing".

The US is ahead of the UK in timing, both in ultra-high stability laboratory devices and miniaturised clocks. JILA's 3D Fermi gas strontium optical lattice clock promises stability of 3×10^{-20}, about three orders of magnitude better than anything in the UK. DARPA's CSAC is a pioneering chip-scale atomic clock with 5 x 10^{-11} stability that has been available for several years. Teledyne-e2v and NPL are pursuing a UK version.

The UK programme is well advanced in what we define as sensing and imaging, including applications of single-photon cameras, cold atom gravimetry, diamond NV for navigation, and vapour cell magnetometry for brain scanning. The US seems to be less active overall in these areas, although there is considerable academic sensing activity in groups centred around Boulder. JILA has spun out ColdQuanta to cater to the research community with atom/ion ready-made solutions. Vector Atomic Quantum Sensors is another spin-out working on position navigation and timing (PNT), while AOSense is working to commercialise cold atom technologies for PNT. Lincoln Laboratory is investigating both cold atom and diamond NV sensors. Stanford, meanwhile, is pioneering quantum imaging technologies including multipass transmission electron microscopy.

4.2 Facilities

Unlike the UK, the US has major systems integrators and materials fabrication facilities. In particular the National Labs provide outstanding facilities and support for US quantum technology, with world-leading fabrication of superconducting circuits at Lincoln Laboratory and ion traps at Sandia Laboratory, as well as the high-power computing facility at Los Alamos.

The UK does have expertise in thin films produced through atomic layer deposition, which may have a long-term advantage over the main US approach (sputtering) for superconducting technologies, promising better control and error avoidance.

General levels of funding in the best labs are higher than in the UK, and the UK has no equivalent facilities to Yale, with several cryogenic platforms across a range of qubit candidates working on scaling and basic research. Optical research is well established in the UK, with a large number of groups pursuing experimental photonic quantum science.

By comparison with the US, there is little philanthropy in the UK to support buildings and costly high-tech facilities, and limited funding for capital equipment, with EPSRC requirements for 50% co-funding or industrial support being difficult to meet.

4.3 Intellectual Property

QED-C is designed to create a pre-competitive space that generates and shares intellectual property (IP) while complying with competition law. However, different US funding agencies expect different IPR ownership arrangements, creating complexity. Meanwhile, US national labs are fully funded by the state and prohibited from doing business (unlike the UK). So they do not sit on their IP and are happy for US companies to adopt their research.

The UK acceptance of common approaches to IPR ownership and licensing in collaborative projects seems to be advantageous. In the UK, the Lambert Toolkit is made available to research institutions and industrial partners to aid negotiations over IP in collaborations. It cuts the time and cost involved by promoting best practice, with materials that include model agreements and a guide to help navigate the decision-making process. However, there is a feeling that strategy across the Hubs could be more robust to protect IP from being bought up.

4.4 Skills and Training

Training is seen as a UK strength. The NSF and Harvard Quantum Initiative were highly positive about CDTs.

One US model that the UK could consider adopting is NSF’s triplet programme, which offers simultaneous industrial and academic mentors for students.

The repeated message from firms is that there is a shortage of people with key skills for quantum technology, but that they do not need more PhDs or even masters-level qualifications. Instead they want engineers and technical staff with enough understanding of quantum systems to be able to deliver critical components and subsystems. There are suggestions that graduates go directly into corporate research and development and bypass time-consuming PhD programmes: industry needs the skills now.

Annex 1

List of UK Participants

September delegation

- Innovate UK
- Oxford Instruments NanoScience
- Oxford University
- RSK
- Rahko
- University College London
- University of York Quantum Communications Hub

The delegation attended the Quantum Tech Congress in Boston on 10 and 11 September 2019, and met with or visited:

Harvard Quantum Initiative
Lincoln Laboratory
Max Planck/Harvard Research Center for Quantum Optics
MIT Center for Theoretical Physics
QED-C
Yale Quantum Institute

November mission
Birmingham Quantum Hub (Quantum Sensors and Metrology)
British Telecom
Element Six Group
ESPRC
Glasgow Quantum Hub (Quantum Imaging)
Innovate UK
Knowledge Transfer Network
National Physical Laboratory
Oxford Instruments NanoScience
Teledyne e2v
University of Southampton and Covesion Ltd
York Quantum Hub (Quantum Communications)

The mission visited or met representatives of:

Air Force National Laboratory
Caltech
ColdQuanta
Department of Defence
Department of Energy
Google
Honeywell
IonQ
JILA
Lockheed Martin
NASA
PsiQ
QED-C
QuSpin
Quantum Thought
Stanford
Rigetti Computing
White House Office of Science and Technology Policy

Annex 2

Abbreviations

AFRL	Air Force Research Laboratory
AQT	Alliance for Quantum Technologies
ARPA-E	Advanced Research Projects Agency-Energy
DARPA	Defense Advanced Research Projects Agency
DHS	Department of Homeland Security
DOE	Department of Energy
DOI	Department of the Interior
DoT	Department of Transportation
IQIM	Institute for Quantum Information and Matter
JPL	Jet Propulsion Labs
KTN	Knowledge Transfer Network
MURI	Multidisciplinary University Research Initiative
NIH	National Institutes of Health
NISQ	Noisy Intermediate-Scale Quantum Computing
NIST	National Institute of Standards and Technology
NQCO	National Quantum Coordination Office
NQI	National Quantum Initiative
NSA	National Security Agency
NSF	National Science Foundation
NVD	Nitrogen-Vacancy Diamond
ODNI	Office of the Director of National Intelligence
OMB	Office of Management and Budget
OSTP	White House Office of Science and Technology Policy
PNT	Position Navigation and Timing
PQC	Post-Quantum Cryptography
QED-C	Quantum Economic Development Consortium
QIS	Quantum Information Science
QKD	Quantum Key Distribution
SBIR	Small Business Innovative Research
SCQIS	Subcommittee on Quantum Information Science
State	Department of State
STTR	Small Business Technology Transfer
UKNQTP	UK National Quantum Technology Programme
USDA	Department of Agriculture

Annex 3

QED-C Signatories

Corporate

- Advanced Research Systems
- Aliro Technologies
- Amazon
- AOSense
- ARM Research
- AT&T
- Atom Computing
- BAE Systems
- Boeing
- Boston Consulting Group
- BP
- Bra-Ket
- CEC Security
- Citi
- ColdQuanta
- Corning
- Cryomech
- D-Wave
- Entanglement Institute
- EZ Form Cable
- Fieldline
- FLIR
- GE Global Research
- General Dynamics Mission Systems
- Google
- Holzworth Instrumentation
- Honeywell
- HPD
- HRL Laboratories
- Hyperion Research
- IBM
- Inside Quantum Technology
- Intel
- IonQ
- Janis Research
- Keysight
- KMLabs
- L3 Harris
- Lake Shore Cryotronics
- Lockheed Martin
- Marki Microwave
- Microchip/Microsemi
- Microsoft
- Montana Instruments
- NuCrypt
- Photodigm
- Photon Spot
- Physical Science Inc
- Psi Quantum
- PQ Secure Technologies
- QC Ware
- QPRI
- Qrypt
- Quantum 1 Group
- Quantum Circuits
- Quantum Computing
- Quantum Design
- Quantum Microwave
- Quantum Opus
- Quantum Semiconductor
- Quantum Thought
- Quantum Xchange
- Qubitekk
- Qulab
- Qunnect
- Raytheon-BBN
- Rigetti Computing
- Riverside Research
- Rydberg Technologies
- Sivananthan Laboratories
- SkyWater Technology Foundry
- Speqtral Quantum Technologies
- SRI International
- Stable Laser Systems
- Strangeworks
- Sumitomo (SHI) Cryogenics
- Takeda
- Toptica
- Twinleaf
- United Technologies Research Center
- US Advanced Computing Infrastructure
- Vescent Photonics
- Wells Fargo
- Young Basile Hanlon & MacFarlane, PC
- Zapata Computing
- Zyvex Labs

Academic

- Caltech/INQNET
- Colorado School of Mines
- George Mason University
- Georgia Institute of Technology
- Purdue University
- Rochester Institute of Technology
- Southern Methodist University
- Stanford
- SUNY Polytechnic Institute
- University of Arizona
- University of Buffalo
- University of Chicago
- University of Colorado
- University of Maryland
- University of Oklahoma
- University of Wisconsin

Other

- American Physical Society
- Federal Reserve Bank of Philadelphia
- OSA
- SEMI
- SPIE
- SLAC National Accelerator Laboratory
- Universities Space Research Association


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