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## UK national quantum technology programme

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# Quantum Science and Technology



## PERSPECTIVE

### UK national quantum technology programme

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#### Abstract

The UK has, through a mix of government and industry funding, committed more than £1Bn over ten years to a coordinated programme in quantum technology. Five years into this programme, the UK National Quantum Technology Programme has induced a step change in the nation's capabilities for establishing a new sector in future quantum information technologies. We describe how the programme arose and the activities it has supported and influenced to deliver these new capabilities, building on a first phase of over £385M investment across several UK government agencies. As the programme enters its second phase, with a further substantial investment by UK government and global industries, we review the prospects for ensuring the advanced quantum science and demonstrator platforms in imaging, sensing, timing, communications and computing developed over the past five years drive the formation of the sector and embed quantum tech in a broad range of industries by means of new products and services.

#### Introduction

For decades the peculiar behaviour of the quantum world seemed merely an intellectual curiosity, but it is now set to transform everyday technology. World-wide activity has been dramatically enhanced. We in the UK are resourced to harness it to develop a wealth of new devices, including cameras that can see around corners, sensitive gravity detectors, quantum simulators, powerful new kinds of computers and miniature atomic clocks. Quantum technology will soon be in your pocket. More than 5 years ago the UK entered a global race to industrialise this new technology, thanks to the National Quantum Technology Programme (NQTP), an alliance of academia, industry and government brought together to exploit our research strengths. We will describe here how the UK programme was developed, its progress and future aspirations [1].

Quantum technology for us offers new applications in sensing, timing, imaging, communications, quantum simulation and computing, arising from the exquisite control of quantum systems that had developed over the latter half of the 20th century, and the understanding that useful large-scale quantum systems could be built by careful construction of redundancy to mitigate the effects of the environment. The well-known synergy of science and technology, by which new science gives rise to new instruments, and new instruments give rise to new science, found a clear expression in the emergence of this area of technology in the UK, in the form of a long-term programme of science and early technology development funding.

It was clear not only to the scientists but also to UK funding agencies and policy makers that UK quantum science had matured sufficiently for us to know what was feasible in technology commercialisation. Applications became clear, and some of these quite rapidly attracted the attention of companies. These developments were sufficient to stimulate attention in industry to consider what implications this would have for their businesses. Among the early expressions of interest were key users of the technologies, such as government agencies. The area also attracted system integrators for advanced technologies, and soon also venture funders considering the more distant future business landscape.

Further, basic technologies had advanced to the point that it became plausible to take on the significant engineering tasks that would open up new applications, meaning that the opportunity for new products became

evident. As major IT companies in the USA began investing, it became evident that there was a serious interest in the capabilities offered by a quantum computer, and this stimulated interest in building one.

## The UK NQTP

A prerequisite for a large-scale enhancement in UK government support for quantum technology depended on demonstrated strengths of UK quantum *science*, identified by international review. This had been undertaken during the first decade of the 21st century, focusing on UK sector share of highly cited papers and identification of how lively the field was and our position world-wide. Once this had become a priority area for the UK research councils (and especially EPSRC), it was necessary to engage with the UK political leadership. Ministerial briefings (and especially of the then UK Science Minister David Willets) was critically important. The next stage was to convince Her Majesty's Treasury (the UK government finance ministry) of the economic advantage that could accrue from substantial investment in the area. The timing for all this was opportune: the UK community had identified quantum as an emerging technology just as the government was launching its Technology Strategy. That programme sought to develop eight key technology sectors within the UK, to which were added quantum technology and 'the Internet of Things'. The opportunity was seized to add quantum to this list with a focussed, ambitious and transformative vision.

Driven by the efforts of a number of individuals, the UK government announced the NQTP in 2013 in order to take quantum information *science* in the UK toward a quantum technology that would provide new, world-leading information processing technology and seed a tech sector that would open new business opportunities and create economic opportunity for the UK. Community meetings and an open call for delivery mechanisms allowed a start at scale a year after the initial announcement.

The original programme covered research, training and skills and application, bringing together academic, industry and government partners, with an increasing interest from an extended user base, keen to explore what the emerging tech could offer for their businesses. A strong feature of the UK NQTP was an integrated partnership approach bringing all the stakeholders together to allow strategic common investment decisions: from the outset the programme involved the research councils, the National Physical Laboratory, the Knowledge Transfer Network, the Ministry of Defence, and what became Innovate UK and the National Cyber Security Centre. A funding proposal call was issued focussing on the key areas identified at a number of workshops and especially at the Royal Society's Chicheley Hall: imaging, sensing, communications and quantum information processing. At an early stage it was decided to develop a 'hub and spoke' model for the programme to ensure wide engagement.

After extensive peer review four hubs involving nearly 30 universities plus associated companies and government organisations were supported. The four research 'Hubs'—multi-institutional, multi-investigator, challenge-led, focussed research programmes, comprising academic with industry and government partners—that spanned the known areas in which quantum will have an impact: imaging, ultra-precise sensors, secure communications and new quantum concepts for computers were led by Universities:

- Imaging (QuanTIC; Glasgow), led by S Beaumont and M Padgett
- Sensors and Metrology (Birmingham); led by K Bongs
- Communications (York); led by T Spiller
- Computing and Simulation (Networked Quantum Information Technologies NQIT; Oxford), led by I Walmsley

Each Hub, selected through a peer review competition, had a remit to take the best laboratory concepts and use them to develop and demonstrate new applications, as well as pushing the hardware to a point where it would be possible to generate industry interest [2–5].

The partner alliance mentioned above was a very positive element in developing a strategy and roadmap; as part of this alliance a Strategic Advisory Board was formed led for the first five years by David Delpy, the outgoing Chief Executive of EPSRC, the main responsible research council that pushed through the funding bid. This board contained leading researchers, government scientists and officials and industry leaders.

By 2016 the UK spend profile, by then grown to £380M over the five years to 2019, looked as shown in figure 1, in terms of Hub capital and recurrent, training and skills, quantum demonstrator projects led by the UK's Defence Science and Technology Laboratory of the Ministry of Defence, and the Quantum Metrology Institute of the National Physical Laboratory, together with a programme funded by Innovate UK working with industry and a contribution to the European coordination programme *Quanterra*.

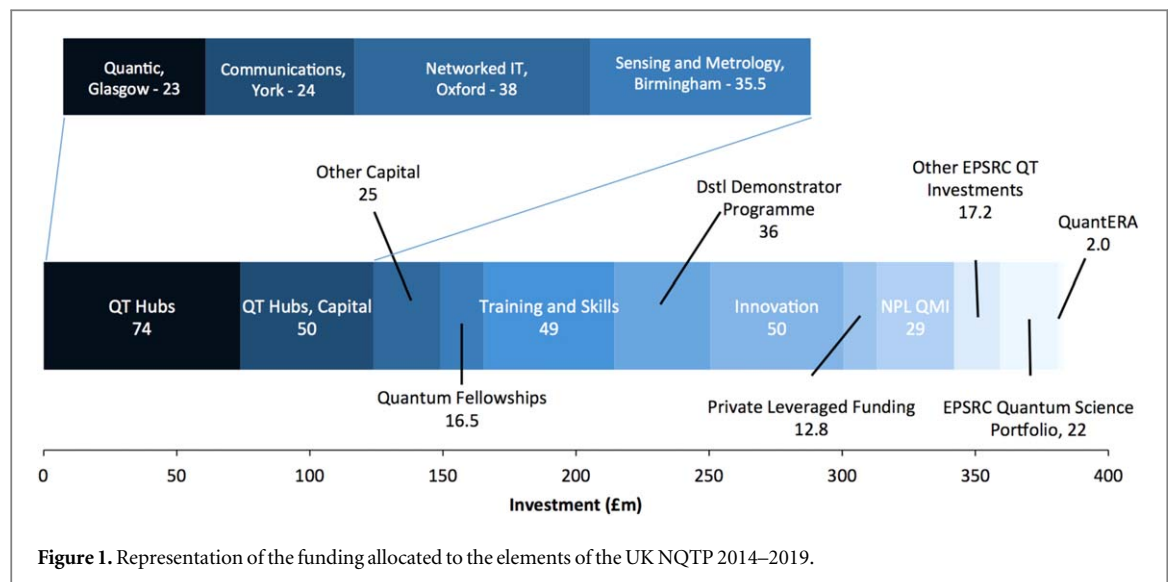


Figure 1. Representation of the funding allocated to the elements of the UK NQTP 2014–2019.

It was recognised early that a skilled base of researchers and engineers versed in quantum technology was critical if a new sector was to emerge and grow. Therefore Skill Hubs were also set up at key universities, again by competition, including The Centre for Quantum Science and Engineering (Imperial College London); Centre for Delivering Quantum Technologies (University College London) and Quantum Technology Enterprise Centre (University of Bristol). Further, several senior research fellows were appointed to provide the full-time ideas leadership that would drive some areas, both in the development of new concepts and the performance of components, as well as in algorithms, protocols and applications. Collaborative technology development projects were seeded in businesses through an industry-focussed innovation fund led by Innovate UK. An annual National Quantum Technologies Showcase in the autumn in central London demonstrated the rapid development of the initiative. Outreach to the general public was a strong feature of the coordinated action [6].

The programme was set up on an ambitious vision for the sector, and the research and development partners were encouraged to frame a bold agenda. Indeed, the tasks set by the research Hubs were always geared toward an objective that was beyond the initial phase of the national funding. This was indeed recognised by the government, which, based on the successes of the first phase, announced in 2018 the second phase of the programme, enabling this longer-term vision to be fulfilled.

The second phase which will start at the end of 2019 (at a similar annual spend profile for a further 5 years), will build on the first phase by refreshing the research Hubs to revise the agendas based on global, as well as national, developments in the field over the past five years. That involved defining a scope derived from an assessment of the sector and on existing UK strengths, and bringing in new partners (both academic and industrial) to broaden and consolidate the current projects. The largest enhancement in our second phase concerns the engagement with industry through the UK Industrial Strategy Challenge Fund (ISCF). A pilot scheme started in 2018 focussing on four industry-led challenges in the competition with £20M of government funding from Innovate UK and matched funding from industry. The aim was to explore the production of prototype devices that provide breakthrough capabilities to answer key end user challenges in sensing and secure information exchange. The four quantum technology ISCF areas in this initial pilot were:

1. *Situational Awareness*: Situational awareness during transportation in highly hazardous conditions (e.g. darkness, fog or dust) that is as safe or safer than, that in normal.
2. *Infrastructure Productivity*: Increased productivity in the deployment, improvement or maintenance of the built environment and critical national.
3. *Seeing the Invisible*: Identification and understanding of features and states in key critical areas (medical, environmental, security) which are impossible to access by conventional means.
4. *Trusted Peer to Peer Communication*: Complete and long term trust in the secure peer to peer transfer of data and information (e.g. across smart cities and environments).

Note that these four challenge areas focussed on capabilities and impact, not on the science enablers. The success of this pilot industry engagement programme allowed us to bid for a further extended ISCF support for quantum technology and on Monday 10th June 2019 the UK Prime Minister announced a further £153M of

government support with an industry commitment of £205M. The competition to use this new resource will commence soon and industry-led consortia are already forming. This new commitment moves us beyond the four areas in the pilot scheme to cover all the areas within the UK NQTP.

The UK Quantum Sensors programme expanded in the second phase to enhanced work, for instance, on atomic clocks for navigation, communications took on the task of implementing a real-world test bed for secure key distribution, and NQIT evolved to become a Hub for Quantum Computing and Simulation, with an increased portfolio of platforms that will enable both NISQ and scalable computing machines, as well as emphasising UK strengths in networked ion traps.

In figure 2 below (in a highly non-geographic representation) we show how the complex ecosystem of Hubs and linked universities has developed in the UK in this coordinated programme.

We now turn to a description of the key focus areas within the UK NQTP:

## Quantum sensors

New sensor systems will give us the ability to detect and visualise movement, light, gas emission, electric fields, and even gravity, with unparalleled precision, which could impact on fields as diverse as medical imaging and oil exploration. Sensors are used in everyday technologies to detect motion, sound, and light. They range from the billions of low-cost motion sensors in mobile phones to high-end systems in healthcare and Earth observation. Quantum sensors offer a step change in performance: more sensitive, accurate and stable than current technology.

For instance, quantum sensors based on cold atoms can detect very small changes in local gravity by means of interferometry at the scale of the atomic centre of mass wavelength. Gravity cannot be screened, so detecting buried features due to minute variations in gravity becomes entirely possible. The technique has applications in industry sectors as diverse as civil engineering and oil and gas.

The UK Quantum Sensors and Metrology Hub is developing compact, portable and robust ‘optical clocks’ with significantly greater precision than currently available as well as atomic magnetic sensors that are precise enough to pick up tiny magnetic fields associated with brain activity or cell communications.

## Quantum communications

Communications systems based on quantum components offer levels of security potentially beyond that which we can achieve now, which will allow us to transfer sensitive information with confidence. The fundamental laws of quantum physics guarantee unbreakable encryption provided instruments are properly employed. This has been an area where the UK community has been active for three decades and was an obvious theme from the outset of our programme.

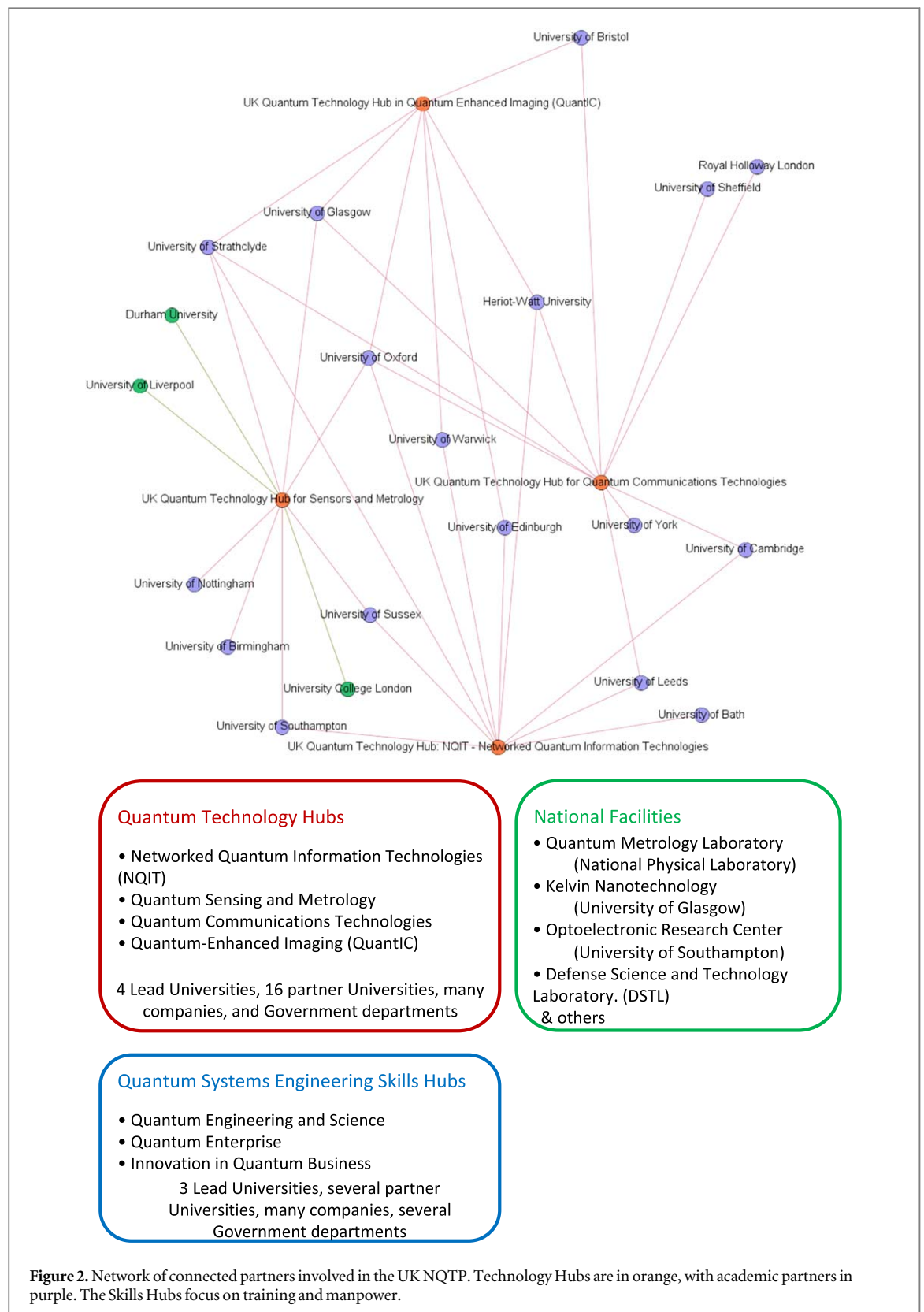
Cryptography is employed by all of us, for example in securing internet messaging: it relies on distributing a secret key—a series of numbers that enable the sender and receiver to encode and decode a secret message.

Public key (PK) cryptography is used ubiquitously for digital signatures and for key establishment. It involves each user holding a private key and an associated PK. The security of PK cryptography systems depends on it being infeasible to compute the private key associated with some PK. The existence of quantum computers presents a real risk to the security of the PK system. In particular, Shor’s algorithm is an efficient quantum algorithm for recovering private keys from PKs for well-known and widely used algorithms that rely on the difficulty of factoring large numbers, such as RSA.

Since Shor shows that the threat cannot be mitigated by using larger keys it is critical to end reliance upon cryptographic primitives that are vulnerable to it: ‘quantum safe’ coding needed to be developed with some urgency.

Secure keys remain essential for today’s computerised financial transactions. Quantum systems provide one vehicle, quantum key distribution, which relies on a central tenet of quantum mechanics, the Uncertainty Principle, says that a quantum system cannot be measured without disturbing it, nor can an arbitrary quantum state be copied exactly (the ‘no-cloning principle’). This means that eavesdropping on a quantum-encrypted communication can be detected. Quantum systems have characteristics that lend themselves to sending information securely. The information they store cannot be measured or copied without being disturbed, which means that any eavesdropping would be detected. Security of information is ensured by the laws of physics, regardless of technological advances. Typically quantum communication systems encode information in individual photons, producing a binary sequence of data. These can then be sent via conventional fibre optics to a receiver. Quantum systems usually use conventional encryption to protect the message, and quantum technology to transmit the cryptographic key needed to decipher the message. Research is focused on several areas, including: ensuring that implementation does not introduce vulnerabilities and developing





intercontinental satellite communications. In 2016 China launched the first quantum-enabled satellite, with the aim of creating a worldwide network by 2030. The UK programme is active in space-based quantum communication and has recently supported a joint UK-Singapore project using cubesat demonstrators.

Post-Quantum PK Cryptography (or Quantum Safe encryption) is being actively investigated within the UK NQTP and the York Quantum Communications Hub is actively engaged in both, as part of their programme on vulnerabilities and resilience. Various different kinds of mathematical structure have been suggested for building post-quantum PK primitives. Each kind of structure requires acceptance of some computational-hardness

assumptions associated with that structure. The UK National Cyber Security Centre partner believes that a transition from current PK Cryptography to Post-Quantum PK Cryptography will be the most appropriate way forward for the majority of high end Government users of cryptographic solutions.

The UK Quantum Communications Hub is building metro-scale networks in Bristol and Cambridge and linking these via the UK National Dark Fibre Infrastructure Service, and on to BT Adastral Park near Ipswich, to form the UK Quantum Network. This national facility will be used for device and system trials, integration of quantum and conventional communications, and demonstrations for stakeholders, end users and the wider public.

## Imaging

Exploiting quantum mechanics has enabled us to make cameras that provide new forms of imaging and this is the focus of the Glasgow-led QuantIC hub. Single photon avalanche detectors (SPAD) enable tremendous developments. A camera based on arrays of SPADs can detect single photons efficiently with short exposure times. These devices can exploit photon timing to see in 3D, look around corners, and make images at wavelengths where normal cameras do not work (including Short Wavelength Infrared able to see through fog, mist and sandstorms). The UK automotive sector is already engaged in evaluating these new capabilities.

Laser range finders are commonplace in construction and defence. The time it takes for a laser pulse to scatter from an object and return to the source gives a highly accurate measure of distance. In defence, it is desirable that the laser illumination is not detectable by anyone other than the sender, which can be achieved with quantum imaging employing pairs of photons. One photon acts as a trigger, alerting the user to the emission of a second photon, which is then sent to bounce off the target. Knowing exactly when the photon was produced allows ranging of objects with low intensity light, undetectable by anyone else.

## Quantum information processing

The toughest number-crunching problems are currently tackled by supercomputers, but some problems are too difficult to solve with foreseeable resources or in a reasonable time. Quantum computers will give us a capability to overcome these challenges by tackling problems in an entirely different manner. We have relied on continuing increases in computational capability for some decades through exploitation of nanotechnology in semiconductors (Moore's laws) but this progress is likely to slow or stall in the coming decade.

The advantages of quantum computing became clear when Shor at AT&T Bell Laboratories devised a quantum algorithm that could factorise large numbers in a time exponentially faster than a classical algorithm. It could easily break keys used in today's PK encrypted communications, which are based on the multiplication of two prime numbers, with severe implications for national security. IBM's Blue Gene supercomputer would take millions of years to factor a 256 bit binary number, whereas a quantum computer working at the same clock speed could do it in a few seconds. For this reason the world economy needs to retool its encryption technology to ensure secure information transmission for transactions etc within a decade; NIST is currently evaluating quantum safe approaches to replace RSA within this timescale and the UK (through the NCSC and involvement in ETSI) is playing an active role in this process.

A quantum search algorithm has been developed by Grover that could speed up the search through databases, searching one million items in just a thousand steps, whereas the best classical search algorithms would take up to a thousand times longer. Many computer operations involve searching. Industrial applications include logistics and optimisation.

NQIT's ambition is to take the world's most advanced quantum prototypes and engineer them into practical technologies. Their focus is on systems that can network together to form flexible, scalable solutions for diverse applications. The network is the single most important concept in modern information technology, with an incalculable transformative impact on society arising from its reliable and efficient connectivity. Quantum networks inherit these features by connecting different quantum subsystems. NQIT has already built small systems that store and manipulate quantum states with exquisite accuracy and we have harnessed light to act as a near perfect information carrier. We are now bringing these together to deliver a suite of *networked quantum information technologies*. Our focus is on quantum **computing** and digital quantum **simulation**, where hitherto impossible tasks will ultimately become possible, and so the eventual societal and economic impact may be greatest; and we will use quantum networks to make radical advances in enhanced distributed sensing and in multi-party communication.

The flagship deliverable of the NQIT Hub is the Q20:20 quantum engine, an optically-linked network of 20 cells, each cell being a quantum processor with 20 matter qubits. Vastly exceeding the complexity of any comparable system, we hope it will give the UK an excellent position in the global race to unlock the full potential

of quantum computation and simulation. Moreover it will require the development of all the elements of a fully scalable fault-tolerant system.

In parallel with our technology development, the Hub will foster the emerging quantum industry through an international effort to define standards for compatibility between systems, training the next generation quantum workforce, getting industry ‘quantum ready’ via several initiatives (one example is the use of quantum computers for space applications with the UK and European Space Agencies), engaging with UK Government on policy and regulation, and encouraging innovation and entrepreneurship with the development of new intellectual property and spinout companies.

### **UK strengths in hardware and software development**

There are currently two technology platforms with the most immediate potential for building a quantum computer: trapped ions interconnected with light, and superconductors connected with microwaves. The UK already has a world-leading position in the first of these, with the best qubits and fastest high-fidelity logic gates (two important metrics for achieving scale), and a strong base in the second. It also has globally competitive or leading activity in several other computing platforms, with the capacity to move ahead should one develop faster. The UK also has considerable strengths in software and algorithm development, witnessed, for example, by the recent Google Prosperity Partnership between UCL, Bristol and Google.

#### *Simulators, annealers and hybrids*

The most promising applications within the next 5 years will be within quantum simulators, annealers and hybrid systems which are enabling users to identify applications and to develop algorithms in advance of scalable quantum computers. Quantum annealers such as the *D*-wave machine are already available for use. These operate in a different way to generic quantum processors and can only be used for specific optimisation problems. However they are enabling algorithms to be developed. The next generation of generic quantum processors will be based on so-called Noisy Intermediate-Scale Quantum Technology (NISQ), NISQ processors will be able to solve important real-world problems in e.g. chemistry, materials science, finance and logistics using a relatively small number (~100–200) of qubits (as opposed to the 10 000–100 000 qubits for a scalable machine). The compromise made is that NISQ processors use no (or very limited) error correction and employ quantum hardware only for those parts of the problem where it is best suited. The UK has now installed an ATOS quantum emulator at the Hartree Centre at the Daresbury Laboratory to enable the community to investigate new quantum software approaches to simulation as a preparatory step in this area.

To build a quantum processor we need:

- qubits (two state systems, quantum analogues of the classical binary bit) that maintain superposition over times long enough to carry out a logic operation by means of a quantum logic gate;
- qubits that can be entangled in a scalable, controllable way, are well characterised and easy to measure, and do not decohere rapidly;
- an architecture that supports an error-correction strategy to maintain a level of fidelity that allows free scaling of the computer;
- different species of qubits that can interact strongly and precisely, so that information can be communicated between systems—via light pulses, voltages or even tiny mechanical vibrations—and stored.

Internationally of course, huge progress has been made in developing quantum processors, both in national and commercial development programmes. For example. IBM, Google and Microsoft are actively developing computing machines based on superconducting quantum logic.

The UK strengths in both trapped ions and photonics offer approaches both to the tens to hundreds of qubits that are needed for a useful simulator, as well as the hundreds of thousands to millions likely needed for a fully scalable fault tolerant computer. The optically networked approach being developed by NQIT (and its successor, the hub for quantum computation and simulation) allows the level of connectivity that, together with gate fidelity and decoherence time, meet the basic requirements for a scalable machine, at the current levels of component performance. Further smaller scale, non-error corrected, processors based on e.g. photonics, are another UK strength, promising early applications within the next decade.

The unique architecture adopted by the UK has the potential to at least equal the performance of the international competition at lower cost and with greater ability to scale.



## National quantum computing centre (NQCC)

It is feasible that the first scalable fault tolerant quantum computer will be built over the next ten years representing the next major step change in digital information technology provision. This opens a new set of economic and societal benefits to early adopters of this technology, based on a strategic sectoral advantage. The UK has made a commitment to realise these benefits by leading the adoption of quantum computing through the establishment of a NQCC announced in the UK government budget in the Autumn of 2018. The NQCC will afford the UK the capability to evaluate, design, develop and build a practical quantum computer, building on the technical and community-building successes of the current NQTP.

In the interim, quantum simulators, noisy intermediate machines are already showing potential applications in the next two–five years that will outstrip classical capabilities. Promising early applications are being explored in areas such as molecular and materials modelling, drug discovery, and complex scheduling, planning and logistics. This is anticipated to create a new multi-billion-dollar global market opportunity. It represents security risks that need to be mitigated against if such computers could break keys used in encrypted communications.

The UK Government is working in two key areas to support quantum computing technology development and capture the benefits for the UK:

- supporting hardware and software development and the growth of the supply chain of component parts through R&D, skills and innovation funding;
- raising awareness of the applications of these technologies for businesses and encouraging early engagement in development to gain competitive advantage.

The NQCC will help position the UK in this area by:

- facilitating UK companies to explore the development and use of quantum computing technology to better understand how it will impact their business and how they may exploit it for their business;
- delivering a value chain by stimulating the complex interactions needed to accelerate emerging technologies and tackle the large number of engineering challenges which need to be overcome in order to build this machine;
- training people both technically and as users, thus establishing a sustainable pipeline of national expertise in quantum computing.

## Public engagement

The UK NQTP recognised from the outset that wider engagement was essential to:

- communicate scientific and technological achievements.
- inspire and inform local, regional, national and global audiences through outreach programmes and social media;
- enter a dialogue with the public to explain the benefits and risks of quantum technologies.

‘Quantum City’ is a flagship outreach programme led by the quantum technology hubs to envision what life might be like when quantum technologies are part of everyday life, describing their impact on areas including healthcare, environment, the economy, communications and Space, with demonstrations and prototypes.

For the vision of ‘Quantum City’ to be realised, the public must agree to the adoption of quantum technologies and understand the benefits and risks they bring. In June 2018, the Engineering and Physical Sciences Research Council (EPSRC) published the results of a public dialogue on Quantum Technologies, which explored the perception of quantum technologies, gathered public experience from diverse backgrounds and sought opinion on application areas [6].

‘Responsible Research and Innovation’ (RRI) is a key component of the UK QTP with training in RRI (such as QuantERA RRI Workshop in October 2017), and seminars focusing on specific sectors. One example of this is the briefing note on ‘Quantum Technologies applied to Defence and National Security’ [7].

## Expectations

The UK NQTP has brought together science, technology and business around a unique opportunity to deliver and exploit a new set of technologies that offer a revolution in capability. These technologies will impact many sectors and communities, from health to security. The UK government has invested significantly to put the UK at the forefront of these developments, recognising that the time is right to accelerate the development of new machines and processes that will eventually change the way we acquire and process information—delivering new concepts, products and services that can be exploited by new and existing companies.

As the UK enters its second five-year phase of funding, it has embraced an ambitious agenda of delivering the ideas, skills, and technologies, from sensors to communications networks to a National Centre for Quantum Computing, that will help to propel the field globally.

## Acknowledgments

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