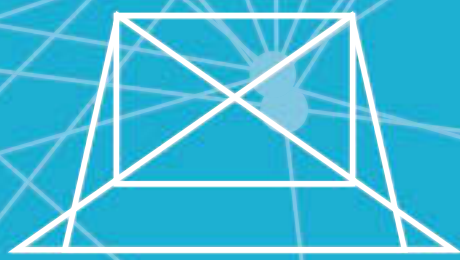




Government  
Office for Science



# The Quantum Age: technological opportunities



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## Foreword

**In a world of exciting technological possibilities, among the most significant are those enabled by quantum physics. It is thanks to this field of research that we have the lasers used in precision manufacturing, the transistors on which today's computers are based and solar cells to provide a clean alternative to fossil fuels.**

The UK is at the forefront of a new era of quantum technologies. Ground-breaking capabilities are emerging from our excellent research and industrial base which will have a profound impact across a range of components including sensors, clocks and microchips. These in turn will support new applications in sectors such as engineering, telecommunications, healthcare, security and finance.

In this report, Professor Sir Mark Walport, the Government Chief Scientific Adviser, analyses these developments and their potential for the UK economy.

In particular, he explains how the convergence of the UK's research base and industry in the National Quantum Technologies Programme provides us with a crucial opportunity to capitalise on our comparative advantage.

This is what a modern industrial strategy means: not an attempt to cling on to the past, but a bold and confident claim to the future.



**Rt Hon Greg Clark MP**  
Secretary of State for Business,  
Energy and Industrial Strategy





## Preface

**There is a global effort under way by the major industrialised nations to translate excellent quantum science from the labs of their research institutions into technology. The UK is currently playing a significant role in this effort, not least in the form of the UK's National Quantum Technologies Programme.**

The timing of this report coincides with the midpoint of that programme, and aims to provide a snapshot of the activities in the UK towards the development of quantum technologies. The report has four main themes focusing on:

- the key areas of quantum technologies under development in the UK
- the advantages quantum technologies could offer over existing technologies – the so-called 'quantum superiority'
- the major sectors that may be impacted by these emerging technologies, while pointing to existing and prospective markets.
- the prospects for commercialisation, taking into consideration the context of the international landscape.

In the course of preparing this report, we have enlisted the knowledge and expertise of a panel of academics and industrialists from across the country, who have provided the evidence base for the chapters. The report also includes a number of case studies which aim to highlight how and why the commercialisation of quantum technologies is being pursued.

We are deeply grateful to the expert panel members for providing these invaluable insights. While representing their own viewpoints, their inputs have greatly informed the themes and the direction of the report.

We have worked hard to make this complex topic comprehensible to non-expert audiences. The challenge of writing in this way about quantum science and technology is that experts will find fault with our simplifications and that non-experts may still find the material incomprehensible! We hope our efforts have

been successful.



*Mark Walport*

**Professor Sir Mark Walport**  
Government Chief Scientific Adviser



*P. Knight*

**Professor Sir Peter Knight**  
Emeritus Professor of Quantum Optics,  
Imperial College London  
Chair of the Quantum Metrology Institute,  
National Physical Laboratory





## Executive Summary

# THE QUANTUM AGE: TECHNOLOGICAL OPPORTUNITIES

**We are living in an information age, encoded in binary 1s and 0s. Arrays of transistors in silicon chips give extraordinary power to modern computers. Microprocessors are embedded in consumer goods and linked via networks, allowing an exchange of information that has led to new service industries.**

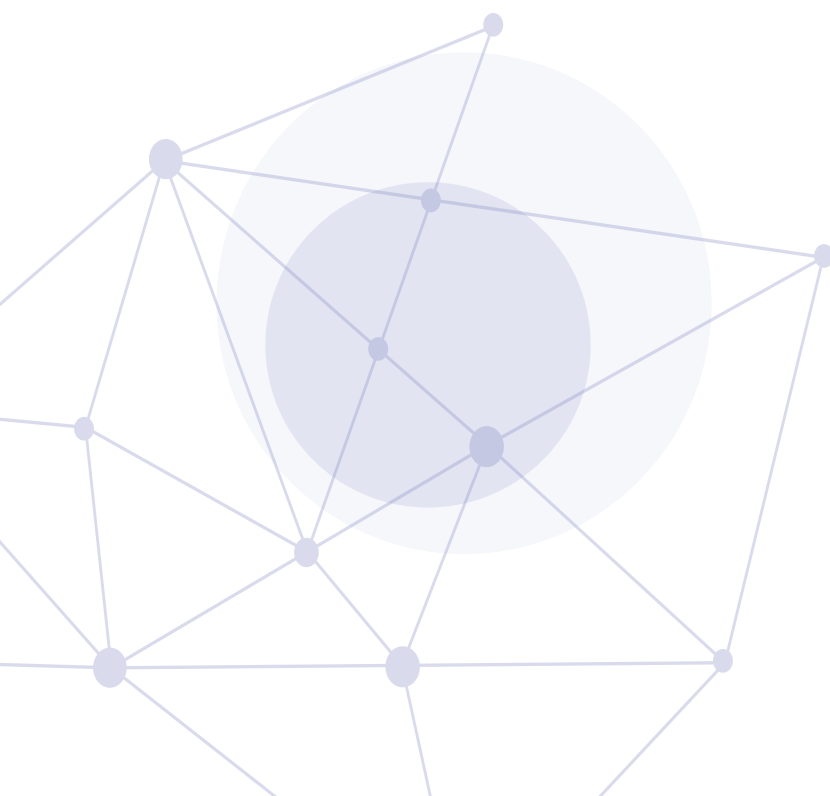
This all stems from revolutionary discoveries around a century ago, when physicists revealed the inner secrets of atoms and the quantum nature of subatomic particles. From the transistor to the mobile phone, from the laser to the magnetic resonance imaging scanner, our understanding of the subatomic world has led to prolific household and industrial technologies that we take for granted.

But what of the future? We are now seeing the emergence of technologies that will take us into a post-digital era. The quantum world is not binary. It is a place where a particle behaves like a wave; where an electron spins in opposite directions at the same time; where information can be encoded as 1, 0 or both 1 and 0 simultaneously; where two particles can be both separated and yet entangled. This report is about emerging quantum technologies that capitalise on these strange and counter-intuitive effects.

You don't need to understand the details of the underlying physics to grasp the potential power of these new quantum technologies. They are set to have a profound impact on our everyday lives, often doing things that are impossible today. Quantum devices could enable us to see around corners, map hidden underground hazards, and easily solve problems that would stump any existing supercomputer.

This report aims to explain the state of the art in quantum technologies, where they show promise and their prospects for the future. It lays out a series of recommendations on how to press forward. Because of investments by the UK Research Councils, the Department of Business, Energy and Industrial Strategy, Innovate UK and the Ministry of Defence, the UK is in a strong global position in the development of novel quantum technologies, in many cases working closely with international partners. Our recommendations are designed to help the UK to get the most from these investments and from our excellent academic and industrial base in quantum science.

There is now a unique opportunity to take a lead in this new generation of technologies. In doing so we can realise their full societal and economic benefits as early as possible.



**Recommendation 1:** *There is a strong case for continuing the UK National Quantum Technologies Programme to maintain our world-leading position in a promising and now globally emerging area of technology. There should be matched private sector investment in any future phase, to increase the level of industry commitment to the programme, and to accelerate the process of commercialisation.*

### THE QUANTUM AGE

The UK economy and wider society depend on advanced technologies such as satellite navigation, smart phones and an energy grid that gives uninterrupted power on demand. At their core these digital technologies are governed by the inescapable laws of quantum physics, which set the rules at the scale of atoms.

A new wave of technologies promises to harness curious quantum effects such as superposition and entanglement (Chapter 1). These effects are extremely sensitive to the outside world, which allows their use to make very accurate measurements of external influences such as gravity or magnetic fields.

Quantum technologies are set to provide much improved capabilities in timing, sensing and measurement, imaging, computing and simulation, and communications. The new technologies, as well as the businesses and services that develop around them, are expected to affect many major sectors including healthcare, defence, aerospace, transport, civil engineering, telecommunications, finance and information technology.

A few of these technologies have already been commercialised. While some of those at the start of the journey may not deliver, others will turn out to be disruptive.

UK academia and industry are working together, and in many cases with international partners, to bring quantum technology products to the global market.

### TIMING

Timekeeping technology has enabled economic advances in the past. In 1714 the UK Parliament passed the Longitude Act, which created a competition to develop a method of determining longitude accurately at sea. The H4 marine chronometer by John Harrison was the most successful timepiece created in response to the

competition<sup>1</sup>. His work led to easier and safer navigation for British merchants and the Royal Navy, which protected the growing British Empire.

Today, timing is more important than ever. Atomic clocks are so accurate that they have been used as a standard of time for nearly half a century, and a new generation of quantum clocks could be several orders of magnitude more accurate still. These clocks will have a wide range of prospective applications across sectors including finance, transport, telecommunications and energy.

There is an international reliance on global navigation satellite systems (GNSS), which depend on space-borne atomic clocks to provide precise timing signals. However, GNSS is vulnerable to failure and disruption, including through deliberate interference. A new generation of quantum clocks can be built into terrestrial systems as a timing backup, to provide resilience against the unavailability or loss of GNSS.

**Recommendation 2:** *Cabinet Office and the Government Office for Science should review the critical services dependent on GNSS timing signals and mitigate the risks by analysing how long they should be capable of operating with back-up or holdover technology.*

We will need new standards for any national infrastructure that is critically dependent on timing equipment and services. These standards should specify what is required to maintain operation of key systems or services without GNSS. Suppliers of critical services, such as telecoms operators, financial institutions and power generation companies, could then be asked to demonstrate that they have the necessary timing infrastructure to meet the new standards.

**Recommendation 3:** *The National Physical Laboratory and the National Cyber Security Centre should support the development of standards for GNSS-resilient timing infrastructure, working with industry, the research community and the relevant standards bodies where appropriate. They should also support the drive for the harmonisation of standards internationally, recognising that in the case of clocks, the applications landscape is complex and involves a number of different standards bodies.*

Financial markets are highly interlinked and increasingly complex, and the time-stamping and traceability of transactions have become fundamentally important. As the pace of trading

increases, more accurate clocks will be required to prevent several separate transactions carrying the same timestamp. A time reference is also essential to synchronise different trading systems and to ensure that transactions are traceable, which helps to protect against fraud.

Investing in a fully optical fibre network linking key locations around the UK would have many benefits, both for manufacturers of atomic clocks and for end-users such as financial markets, by allowing atomic clocks to be checked against national time standards remotely. Such a network could also be a test-bed for technology demonstrator experiments in both the quantum clocks and communications sectors. It would provide the UK with a unique resource on which to build research, innovation and high-value manufacturing.

**Recommendation 4:** *The National Physical Laboratory and the Quantum Communications Hub, working with existing infrastructure organisations, should explore the feasibility of a fully optical fibre network for the purposes of timing and frequency distribution, as well as a test-bed for technology demonstrator experiments. This might start as a city-wide demonstrator project and later expand to key locations around the UK.*

Chapter 2 discusses the applications mentioned above and reveals how new clocks are already starting to make a difference.

## QUANTUM IMAGING

One new ability that captures the imagination is seeing around corners from a distance: researchers have created a quantum imaging system that builds a picture of the environment as viewed from where a laser beam falls. Another system can create a 3D image by measuring the time it takes each photon to travel to and from objects in the scene.

Such technologies will find uses beyond the obvious military and law enforcement applications. They could be integrated into driverless cars, used for emergency rescue in confined or dangerous environments, or built into the monitoring and maintenance of infrastructure.

Other applications are developing out of complementary technologies that add to the suite of sensors and imaging devices available to industry as a whole – for instance, seeing through

smoke, imaging gas leaks, or range-finding using light instead of radar. These applications and more are described in Chapter 3.

## QUANTUM SENSING AND MEASUREMENT

Quantum sensors can offer higher sensitivity, accuracy and speed of use than current technologies, particularly for gravity and magnetic fields. Such sensors work by harnessing quantum effects such as superposition. This area is already yielding working prototypes, which are being developed to compete in the commercial world.

Quantum sensors will enable quick and accurate gravity mapping: detecting minute differences in gravity to reveal underground features. There is much buried beneath our feet, including different soil and rock types, utilities, tunnels and old mineshafts. More detailed information would prove extremely useful in building new infrastructure on brownfield sites; exploring and monitoring natural resources, including water; and identifying hazards such as sinkholes and landslides. Quantum sensors offer a key to unlock the secrets of the underground.

Equally, improved sensing of magnetic fields has important implications for healthcare, offering easier ways to screen for diseases such as dementia, and the early detection of cancer and heart conditions. New quantum sensors do not need the bulky and expensive equipment that some current technologies rely on.

Quantum sensors can also enable on-board inertial sensing for navigation, an alternative to relying on satellite navigation. Chapter 4 describes all these sensors and their abilities.

The market for sensors is expanding with the advent of the Internet of Things<sup>2</sup>, and there is an opportunity for quantum sensors to provide niche capabilities as well as compete with classical<sup>3</sup> technologies. The UK should be flexible and responsive in adapting regulations to accommodate quantum sensors, and indeed other quantum technologies, considering the new capabilities they bring.

**Recommendation 5:** *Regulation should not present a barrier to the use, deployment and commercialisation of quantum technologies. The National Programme should ensure regulators and standards bodies are aware of the capabilities of the technologies under development, so that regulations*

are formulated to realise the full potential of these technologies. Test-beds and road-mapping should be considered as a route to development of the regulations by government.

### QUANTUM COMPUTING AND SIMULATION

Perhaps the most familiar but most misunderstood area of quantum technology is the quantum computer. These machines will not be replacing our laptops in the short to medium term.

At this stage, it is perhaps more useful to think of them as advanced problem solvers and modellers that can tackle and analyse problems inaccessible by conventional computers. There are two very important tasks that a quantum computer is expected to be able to do much more efficiently than conventional computers: factorise large numbers and search through large amounts of unstructured data. Why is this important? The cryptography that underpins the security of many digital services relies on the fact that it is very difficult to find the prime factors of large numbers. So quantum computers that can factorise large numbers readily would have serious security implications. The ability of quantum computers to search unstructured data quickly offers new possibilities in data analytics (such as searching web pages) and fundamental science (such as exploring the human genome).

Quantum computers could also simulate highly complex physical systems, such as new materials, chemical interactions and the effects of pharmaceutical drugs, which are difficult to model even with modern supercomputers.

In May 2016, IBM made a prototype quantum computer available to the general public via the internet. It has enabled computer scientists around the world to test algorithms and programmes they have written to run on a quantum computer. It is, however, only powerful enough to offer proof of concept. Researchers think that a device that can deliver on the promise of quantum computing is between five and twenty years away<sup>4</sup>.

Software is just as important as hardware, and for quantum computers to be more widely used we need to develop algorithms that will allow them to tackle new challenges.

**Recommendation 6:** *The National Quantum Technologies Programme should work with the*

*Alan Turing Institute, the Heilbronn Institute for Mathematical Research and wider academia to identify a set of example challenges which, if solved by a quantum computer or quantum simulator, would have important benefits to government, business and citizens. These challenges would involve algorithm research related to areas such as machine learning, artificial intelligence and the investigation of pharmaceutical drugs and new materials. Government could act as a demonstration client for some of these challenges.*

Chapter 5 takes us through this in more detail and explores what can be done now to prepare the ground for the development of a quantum computer.

### SECURING OUR COMMUNICATIONS

Cryptography underpins the security of our financial, business, government and personal communications. A secure method of communication is therefore essential, not only to governments but also businesses and individuals.

Some forms of encryption in use today are vulnerable to attack by future quantum computers. Furthermore, anything communicated today may be stored and accessed in the future by a hacker armed with a quantum computer. So we need to act now to create new methods of securing our digital information.

There are two ways this might be done. Some cryptographic methods, referred to as post-quantum cryptography (PQC), should be as hard to solve for a quantum computer as for a classical computer. The other option is quantum key distribution (QKD), which uses the quantum properties of light to share a secret key. An eavesdropper can't pick up this key without revealing themselves. As explained in Chapter 6, this is based on the laws of physics rather than the difficulty in decrypting an algorithm. QKD has already been deployed in real-world systems such as Geneva's canton elections in 2007. These two approaches should be researched in tandem.

**Recommendation 7:** *The National Quantum Technologies Programme should fund collaborative work between UK quantum communications and cryptography research groups, leading to joint technical developments of both quantum key distribution (QKD) and post-quantum cryptography*

(PQC), as well as work on digital signatures and other uses of these technologies.

QKD does however need further research to ensure that the application of the technology is cost-effective, practical and secure when deployed across networks, and that the future safety of data encrypted using quantum keys is fully explored.

**Recommendation 8:** *The National Cyber Security Centre should support a pilot trial of QKD using realistic data in a realistic environment, with the facilities for the trial being provided by the Quantum Communications Hub. Such a trial should serve to stimulate the supply chain and show UK leadership in secure communications.*

Standards are important for the interoperability of equipment and services, and also to assure end users of an accepted level of performance. Establishing an independent body to scrutinise products and services would boost confidence in quantum communications technologies. Such a body would need the facilities and expertise to conduct conformance testing, and appropriate authority as a trusted organisation to offer certification.

**Recommendation 9:** *The National Physical Laboratory, the National Cyber Security Centre and academia should form a partnership to perform conformance tests and issue accreditation certificates. This process would need to involve engagement with other interested parties from industry, such as the communications and financial services sectors, and could lead to the establishment of an independent national facility.*

## COMMERCIALISATION – THE UK'S OPPORTUNITY

The UK is well-positioned to remain at the forefront of the new age of quantum technologies, but to do so we must continue to translate our world-class research into practical applications, aligning with markets and industries. Chapter 7 explores these market opportunities and how the UK can capture them.

In 2013 the Government announced an investment of £270 million to develop and commercialise quantum technologies, to place the UK as a leader in the global supply chain. As part of this investment, the Engineering and Physical Sciences Research Council established the National Quantum Technologies Programme (NQTP) and with it the Quantum Technology

Hubs, each of which represents a UK-wide network of academic and industrial partners focused on the areas outlined in this report. These hubs, along with the National Physical Laboratory and industry, are key parts of the mechanism for achieving the aims of the NQTP. As the programme continues it will be important to deepen the involvement of industry (see Recommendation 1).

There are opportunities in the UK not only for manufacturing quantum technologies, but also for developing the services around them and opening up new markets through their enhanced performance.

Additionally, the opportunities and risks of the UK's vote to leave the EU should be considered in relation to the NQTP. Quantum science and application development is happening across the globe and it is important that the programme has an international outlook to take advantage of the opportunities and benefits these engagements bring.

Building on the successes within the NQTP, the next step is to establish dedicated innovation centres which would allow applications for the technologies to be realised through direct engagement with industry. The centres would serve to accelerate the rate at which fundamental science is pulled through into applications tailored to meet end user needs. These centres would provide open forums for active engagement with industry to raise awareness and build confidence in the capabilities of the technologies, eventually stimulating the supply chain in the UK and driving these technologies towards commercial applications.

**Recommendation 10:** *The UK, through a competitive process overseen by the National Quantum Technologies Programme, should establish innovation centres. These centres would go beyond the scope of the current Quantum Technology Hubs, involving the co-location of academic and industrial partners with the requirement for matched funding from industry.*

This mechanism would make knowledge and expertise available to stakeholders. These centres would play a similar role in the UK to Fraunhofer institutes in Germany and elsewhere and the Battelle institutes in the US.

As the programme grows in scope, coordination at a national level will become more important.

**Recommendation II:** *The programme partners in the UK National Quantum Technologies Programme, together with the Quantum Technology Hubs, should establish a body with the funding and sole remit to coordinate activities across the programme more effectively.*

This coordination would include monitoring and adapting to national and international developments, advising on prioritisation and coordination of resources across the programme, linking to horizon-scanning activities across government, and organising strategic projects, competitions and demonstrators such as those currently run by the Small Business Research Initiative.

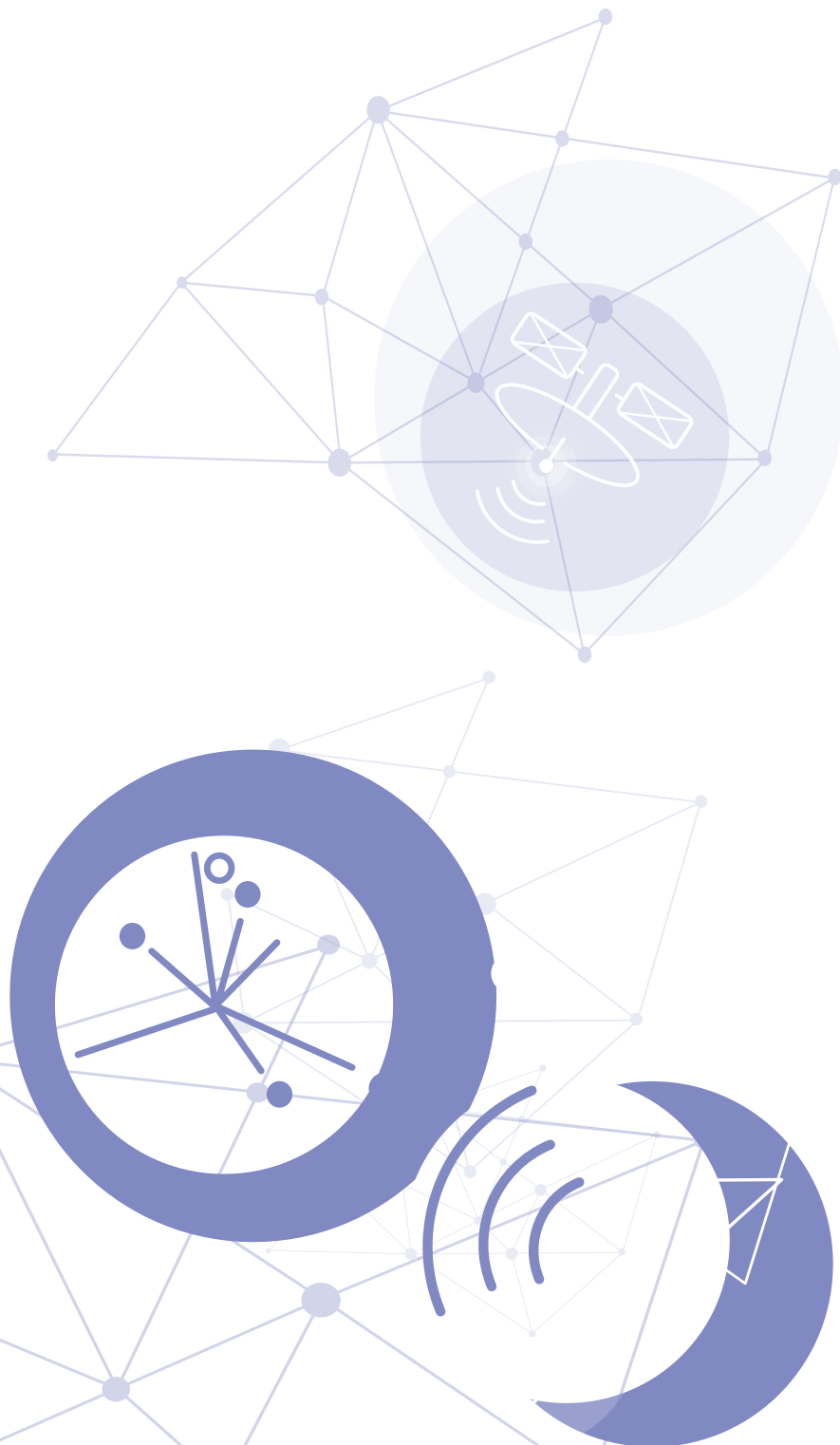
#### WHY NOW?

Quantum technology is with us. The technological opportunities are diverse and developing quickly. Their sensitivity, accuracy and speed as well as improvements in cost, size and weight have reached a tipping point, where further sustained effort from government, academia and industry can help to propel emerging technologies to commercial success. This is an opportunity to develop a world-class industry, supported by a skilled workforce and stimulated by global demand.

We have already set in motion a national programme to develop our industrial base, integrated with UK research in this field, yet we are only at the start of the journey. This report

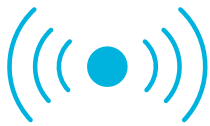
outlines those areas where the UK now needs to focus its efforts to ensure an advantage. The gradual rise of these technologies may be mostly invisible to the consumer, but they will have a huge impact on all of our lives.

#### Mark Walport



**CHAPTER 1:**

# THE SECOND QUANTUM REVOLUTION



Quantum technology is  
the foundation of the  
**DIGITAL AGE**

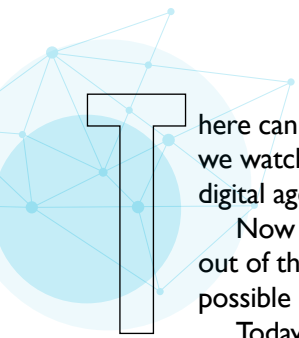
New types of quantum  
technology are coming  
out of the lab that  
surpass anything  
possible before

Producing quantum  
technology components  
could create a

**HIGH-VALUE**  
manufacturing sector



Peter Knight  
Richard Murray  
Jonathan Pritchard



There can be few homes in the UK without quantum devices. We wear them on our wrists, we talk into them, we watch them, and we travel in vehicles controlled by them. Quantum technology is the foundation of the digital age.

Now we are on the verge of a second quantum revolution. New types of quantum technology are coming out of the lab, promising sensing, communications, timing and information processing to surpass anything possible before.

Today the UK has a world-leading position in quantum technologies, but the competition is advancing rapidly and we need to remain agile to turn these ideas and prototypes into commercial gain.

### WHAT IS QUANTUM TECHNOLOGY?

Devices such as transistors and lasers exploit the fact that very small objects, such as electrons in crystals, can have only certain fixed energies.

Now we have the ability to manipulate individual atoms, electrons and other particles. This brings direct benefits, for example in timing the arrival of photons to make a 3D camera, and in some of the most accurate new optical clocks which use single trapped ions or atoms. It also means we can take advantage of counter-intuitive quantum phenomena including entanglement and superposition (see Quantum Basics, opposite page).

Because quantum effects are inherently fragile, they can be used to create exquisitely sensitive and precise devices. The counter-intuitive aspects of quantum physics allow them to perform some tasks not possible in the classical world.

**QUANTUM CLOCKS** based on trapped ions and atoms can measure time with unprecedented accuracy.

**QUANTUM IMAGING** involves the detection and timing of single photons to beat classical limits, making the invisible visible. Novel imaging systems can allow us to look around corners or through fog.

**QUANTUM SENSORS** can enable the detection of motion, light, electric and magnetic fields, and gravity with an accuracy that surpasses many conventional technologies.

**QUANTUM COMPUTING** is expected to perform tasks that are intractable for conventional machines. While IBM's Blue Gene supercomputer would take millions of years to crack common forms of data encryption, future quantum computers should be able to do it in a few seconds. They should also allow us to design materials with completely new properties.

**QUANTUM COMMUNICATIONS** can be secure against hacking, and may enable networked quantum cloud computing.

### MARKETS AND IMPACTS

Quantum technologies have a huge range of applications in many sectors, including:

- **Oil and gas.** Gravity surveys with quantum sensors could aid discovery of oil and gas resources, and increase yields – potentially worth trillions.
- **Environment.** The cost of the 2007 summer floods to England was estimated at £3.2 billion<sup>1</sup>. Quantum sensors for measuring gravity could aid flood prevention by allowing us to monitor the water table more accurately.
- **Data security.** An increasing amount of confidential information is shared on communication networks. The global market for public cloud services is expected to grow by 16.5% in 2016 to more than \$200 billion<sup>2</sup>. Quantum communications can increase data security on networks, reduce theft of sensitive information and promote trust in network-based products and services.
- **Defence and aerospace.** These major exporters are highly dependent on precise navigation, timing and sensing, all of which will be improved by quantum technologies. For example, quantum sensors for gravity might be used to detect buried explosives. The MOD

Quantum communications can be secure against hacking, and may enable networked quantum cloud computing



plans to be a first adopter of the technologies being developed in its major projects, including small atomic clocks, gyros and accelerometers and a gravity imaging system.

- **Civil engineering.** New gravity sensors can also reveal underground structures such as buried pipes and sinkholes.
- **Telecommunications.** Tiny ultra-precise quantum clocks will allow denser communications traffic, and could mitigate against the risk of GPS jamming or failure.
- **Finance.** With an ever increasing need for extremely accurate time stamping, financial markets will also benefit from the new generation of quantum clocks.
- **Cities.** Quantum sensors will enable smarter use of energy, water and other utilities, to achieve higher environmental standards and efficiency.
- **Leisure, security and industry.** These sectors can all benefit from new types of camera that use low light levels, see in 3D and look around corners.

New quantum technologies can benefit the UK in other ways too. Not only will the systems themselves be valuable, but producing the components could also create a high-value-added manufacturing sector. The second quantum revolution is based on several enabling technologies where UK companies and universities already have specialist skills – such as light emitters and detectors, specialist electronic materials, superconductors, lasers, ultra-high vacuum chambers and detectors for individual ions, molecules and atoms.

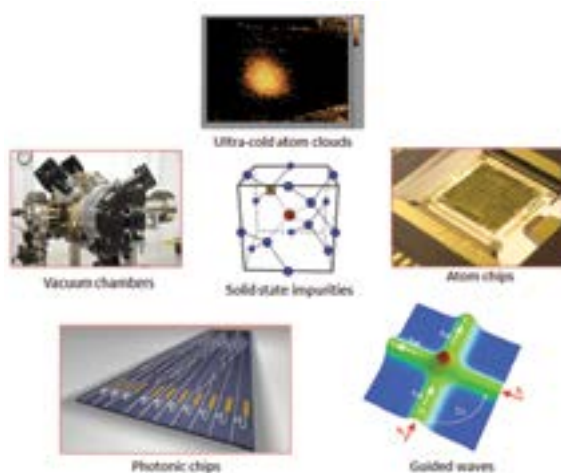


Figure 1: Some systems that enable quantum technologies

## QUANTUM BASICS

Quantum physics is concerned with objects – usually very small ones – that do not behave like the large everyday things described by classical physics.

In classical physics, particles have a precise position and move along well-defined paths. Meanwhile, waves are spread out in space. In quantum physics, the two concepts of particle and wave are combined in the idea of the wavefunction. The wavefunction of an electron or atom defines the probability of finding the particle when you look in a particular place.

Quantum physics tells us that it is impossible to measure simultaneously the precise position and velocity of any particle (the uncertainty principle), and involves other counter-intuitive phenomena including superposition and entanglement.

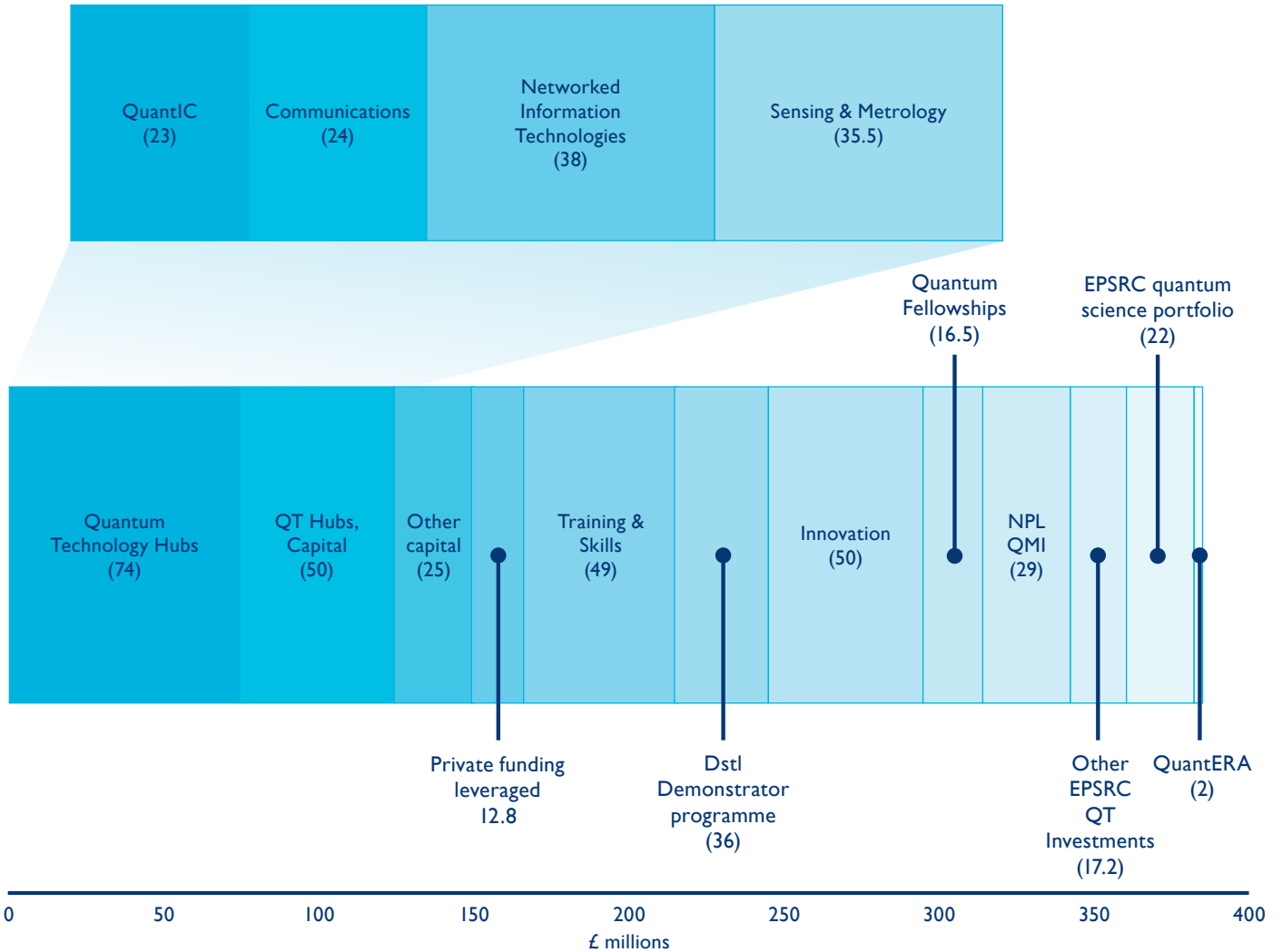
### SUPERPOSITION

A particle can be in two or more states at once. When its state is measured, it settles into one of the possibilities and ambiguity is lost. For example, an electron can be spinning in one direction (say clockwise) and another (anticlockwise) at the same time. When the spin is measured it will be either clockwise or anticlockwise. Superposition makes a difference to the outcome. If a photon hits a beam splitter, its wavefunction will travel along two separate paths simultaneously. When the two parts of the wavefunction are brought back together, they can interfere with each other to affect where the photon is finally detected.

### ENTANGLEMENT

When two quantum objects are entangled, their state can only be described as a whole system, not for the components separately. For example, two atoms may be spinning in opposite directions. If they are entangled, it is not yet determined in a fundamental sense which is spinning in which direction. When a measurement is made on one, the outcome of a measurement on the other is decided – if you see one atom spinning clockwise, you already know that the other atom will be measured spinning anti-clockwise without having to actually make the measurement. This happens even if the two atoms are far apart in time or space.

FIGURE 2. FUNDING FOR THE UK NATIONAL QUANTUM TECHNOLOGY EFFORT



**HOW FAR OFF ARE THE NEW TECHNOLOGIES?**

Some new quantum technologies are already in the market, or close to it. For example, compact atomic clocks will soon be integrated into communications networks for synchronisation. Secure quantum communication systems are used around the world in specific high-value applications, including banking. UK institutions are developing next-generation systems that are more accurate, secure, portable, and efficient than anything that currently exists.

Many quantum sensor and imaging technologies are not far from being a large-scale commercial reality – perhaps five to ten years away. Quantum computing is probably the furthest from market, perhaps ten to fifteen years or more. A more detailed discussion of the underlying technologies being developed in the UK can be found in the “UK Quantum Technology Landscape 2016” report by Till and Pritchard<sup>3</sup>.

**UK GOVERNMENT INVESTMENT**

The UK National Quantum Technologies Programme (NQTP) won investment of £270 million in November 2013 for an initial phase of five years. An ensuing competition saw the establishment of four hubs, led by Birmingham, Glasgow, Oxford and York universities. At the same time, the Defence Science and Technology Laboratory (Dstl) won £30 million from the MOD to develop quantum technologies for defence and security, in projects designed to be complementary to the national programme. The result is a coordinated national effort combining universities, NPL, EPSRC, MOD, GCHQ and Innovate UK.

**INTERNATIONAL INVESTMENT**

China is expending an immense effort in quantum science and technology. The US has a huge research base but is less well developed in applications. The

EU has recently released its quantum manifesto, and plans to launch a flagship quantum technology initiative in 2018 within the European Horizon 2020 research and innovation framework.

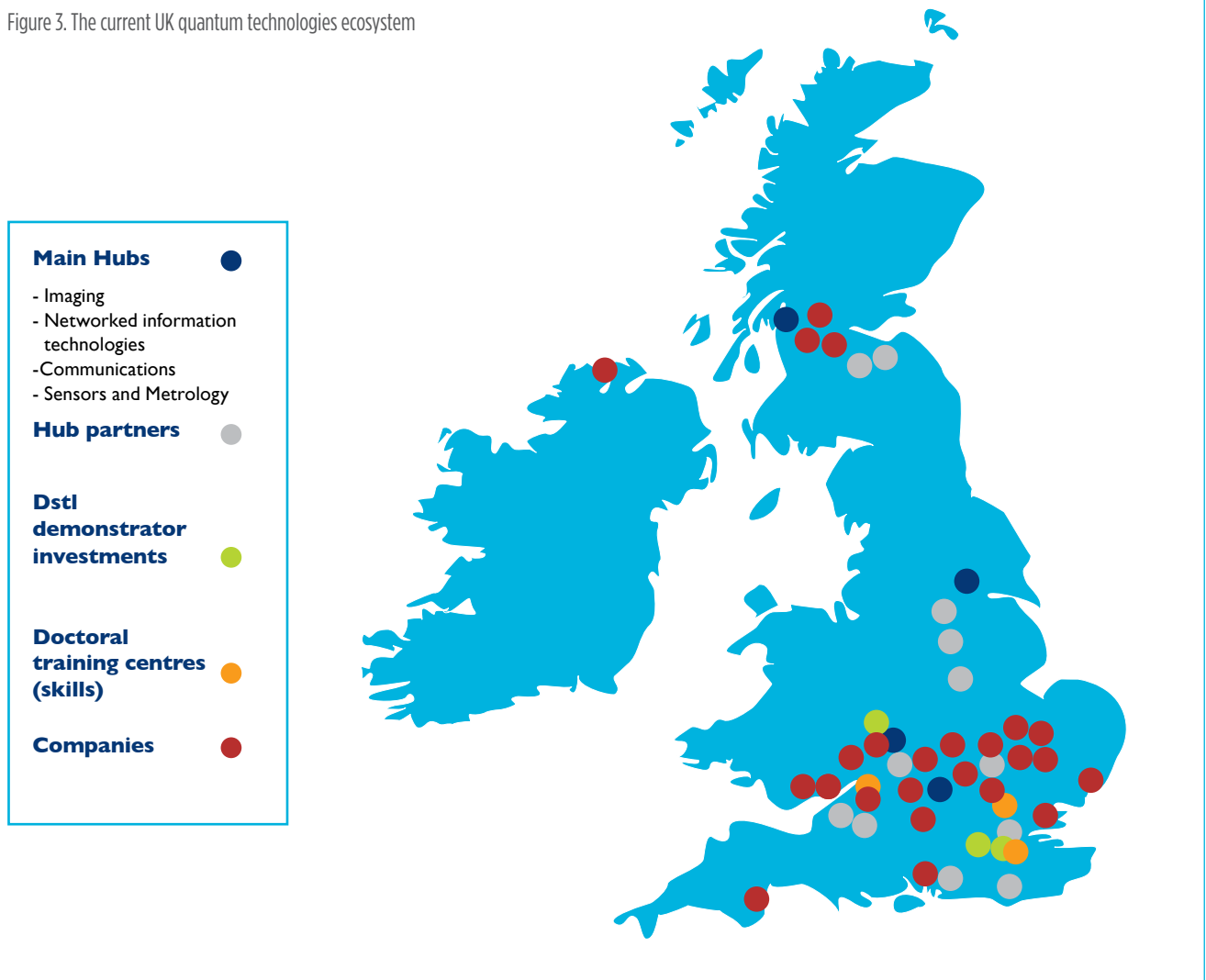
Singapore has invested in its Centre for Quantum Technologies with a broad spectrum of activities. Australia is supporting two major centres of excellence in quantum technology. Canada has established centres in Waterloo and in Calgary with substantial philanthropic support. The Dutch government is investing substantially in its QuTech Centre in Delft, and the Danish Government has set up its QuBiz Centre: both of these focus on quantum computing, and have substantial industrial engagement.

As well as being aware of the threat from competition, we should be open to engaging with national programmes, to foster the UK's development of quantum technology and encourage inward investment.

## CONCLUSIONS

Creating new technology takes time, and demands sustained collaboration between large institutions. But the potential pay-off is great. The government has already made a substantial investment in the quantum technology research base: now we have the opportunity to exploit that early investment. With the international competition in hot pursuit, we must rise to the challenge or be left behind in areas that will become crucial to our economic progress.

Figure 3. The current UK quantum technologies ecosystem



# MAXIMISING THE BENEFIT THROUGH INTERNATIONAL ENGAGEMENT

The UK is not alone in recognising the potential value of quantum technologies.

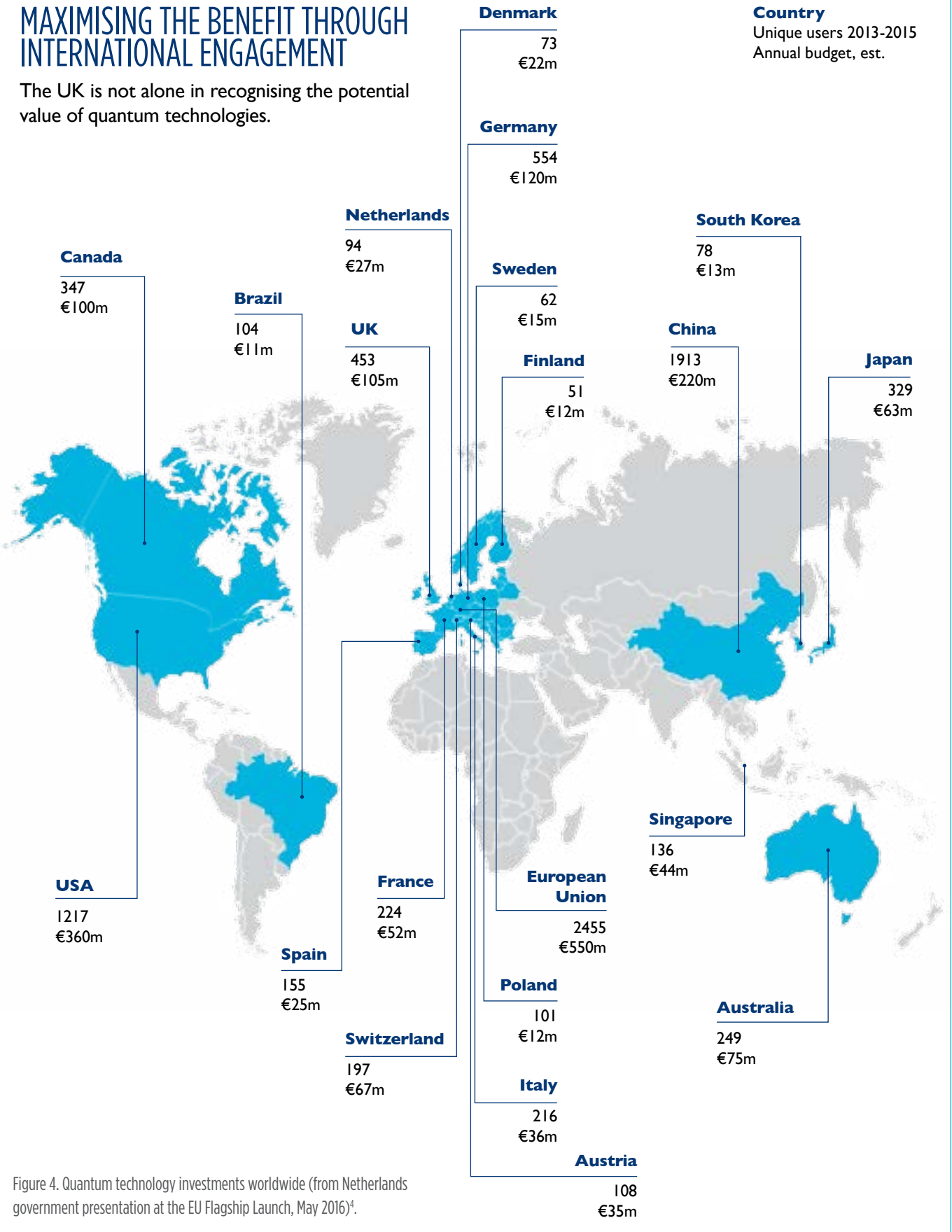


Figure 4. Quantum technology investments worldwide (from Netherlands government presentation at the EU Flagship Launch, May 2016)<sup>4</sup>.

## CHAPTER 2: QUANTUM CLOCKS



Atomic clocks have been used for international timekeeping since

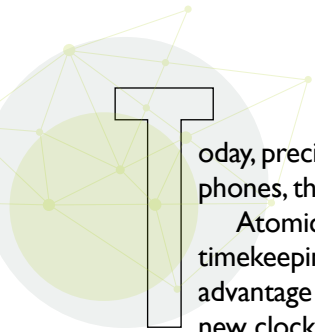
**1967**



The UK played a leading role in the development of the caesium atomic clock – now the international standard for time

The best atomic clocks are now accurate to within a few nanoseconds per century

Helen Margolis  
Trevor Cross



Today, precision timing underpins much of our lives. Technologies that we take for granted, such as mobile phones, the internet and satellite navigation systems, all depend on atomic clocks.

Atomic clocks are the most established kind of quantum technology, used since 1967 for international timekeeping. The UK played a leading role in the development of the first caesium atomic clock, but lost its advantage when the technology was commercialised in the USA. Today the UK is a leader again, developing new clock technologies that are ripe for commercialisation.

The performance of atomic clocks has reached remarkable levels. The best are accurate to within a few nanoseconds per century. Others are small, cheap and portable. These developments are opening up entirely new applications and markets. The new generation of atomic clocks could also guard against our increased vulnerability to disruptions in satellite timing signals.

### WHAT ARE ATOMIC CLOCKS?

All clocks need a regular rhythm to mark the passage of time. It may be provided by a pendulum in a mechanical clock or a quartz crystal in a digital watch. Atomic clocks use certain types of atom to perform this function. The atoms absorb light or microwaves at very precise frequencies which can be measured. The frequency tells you how many cycles are completed in a given time, and each of these cycles (the oscillation period of the light) acts like the tick of a clock: a regular and repeatable slice of time.

Many atomic clocks, including the earliest generation, operate at microwave frequencies. More recently, optical atomic clocks have been developed that operate with visible or ultraviolet light. The higher-frequency optical clocks have the potential to provide a more stable time signal, although microwave technologies are still being improved.

### GNSS VULNERABILITY

We are increasingly reliant on GPS and other global navigation satellite systems (GNSS), which are vulnerable to failure and disruption. Threats include faulty data uploads (see right), deliberate interference due to jamming or spoofing of signals, and solar superstorms, which could disrupt the entire system.

GNSS time signals are used in a vast range of critical applications, from navigation and communication to financial trading and electric power grids. Most of these have no backup systems.

The Royal Academy of Engineering (RAE) has warned of the risks associated with this over-reliance on GNSS<sup>1</sup>. They caution that an interruption to GNSS signals could cause the simultaneous failure of services that need to

## GLOBAL IMPACT OF SATELLITE TIMING DISRUPTION

During the planned decommission of an aging satellite on 26th January 2016, an erroneous software upload by the US Air Force triggered problems for the Global Positioning System (GPS) network. Fifteen satellites started broadcasting timing signals that were off by 13 microseconds. Although this might seem like a tiny error, it had global impact, and for about 12 hours it disrupted GPS-dependent timing equipment around the world.

Suppliers of GPS-reliant technology were inundated with calls, as engineers from the communications industry were called out to respond to the escalating alarms as timing equipment switched into holdover mode. The fault was observed in electric power grids, and the BBC reported problems with digital radio broadcasts as transmitters became desynchronised.

This time, the problem was resolved before the consequences became too severe – but it is a stark warning of what could happen if a major solar storm disabled all GNSS timing availability for a longer period. GNSS-resilient timing solutions are not a luxury; they are essential.



work together in an emergency. In the event of extreme space weather, the RAE recommend that critical infrastructure, communication and safety systems should be designed to operate without GNSS timing for up to three days<sup>2</sup>.

The most resilient solution is to embed atomic clocks throughout each network. This is an important driver for the development of miniature, low cost atomic clocks within the UK National Quantum Technologies Programme and similar initiatives, for example in the EU and the US.

### MARKET AREAS

**TELECOMMUNICATIONS NETWORKS** need time sources that are accurate, stable and reliable. Information is sent in packets, usually via several networks, to be stitched back together at its final destination. If the different networks are not operating at exactly the same rate, data can be lost or the efficiency can be degraded. So international standards have been set to impose limits on the difference in network rates<sup>3</sup>. At present these standards are usually met using GNSS timing. To improve resilience, ground-based clocks are required.

Traffic demands on mobile telecom networks are predicted to increase rapidly<sup>4</sup>, while the number of connected devices is increasing exponentially as billions of wirelessly connected sensors are deployed in the Internet of Things. This puts more stringent demands on timing and synchronisation technologies for next-generation networks, 5G and beyond.

**ELECTRICITY DISTRIBUTION NETWORKS** also need precise timing to keep supplies synchronised when different sources of electricity are combined. The need to keep our energy supply secure, reliable and affordable is leading to radical changes in infrastructure, with smart grids meaning that accurate timing and synchronisation are becoming more critical than ever before.

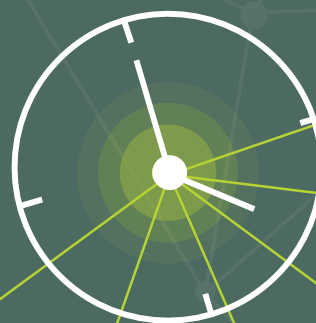
**FINANCIAL MARKETS** use timing signals to synchronise trading systems and produce a record of when each trade happened. The rapid expansion of computer-based trading has increased the need for synchronisation and traceability to a common reference timescale, to help prevent trading irregularities and provide an audit trail. In the UK, this has led to the introduction of

## CLOCK-BASED GEODESY

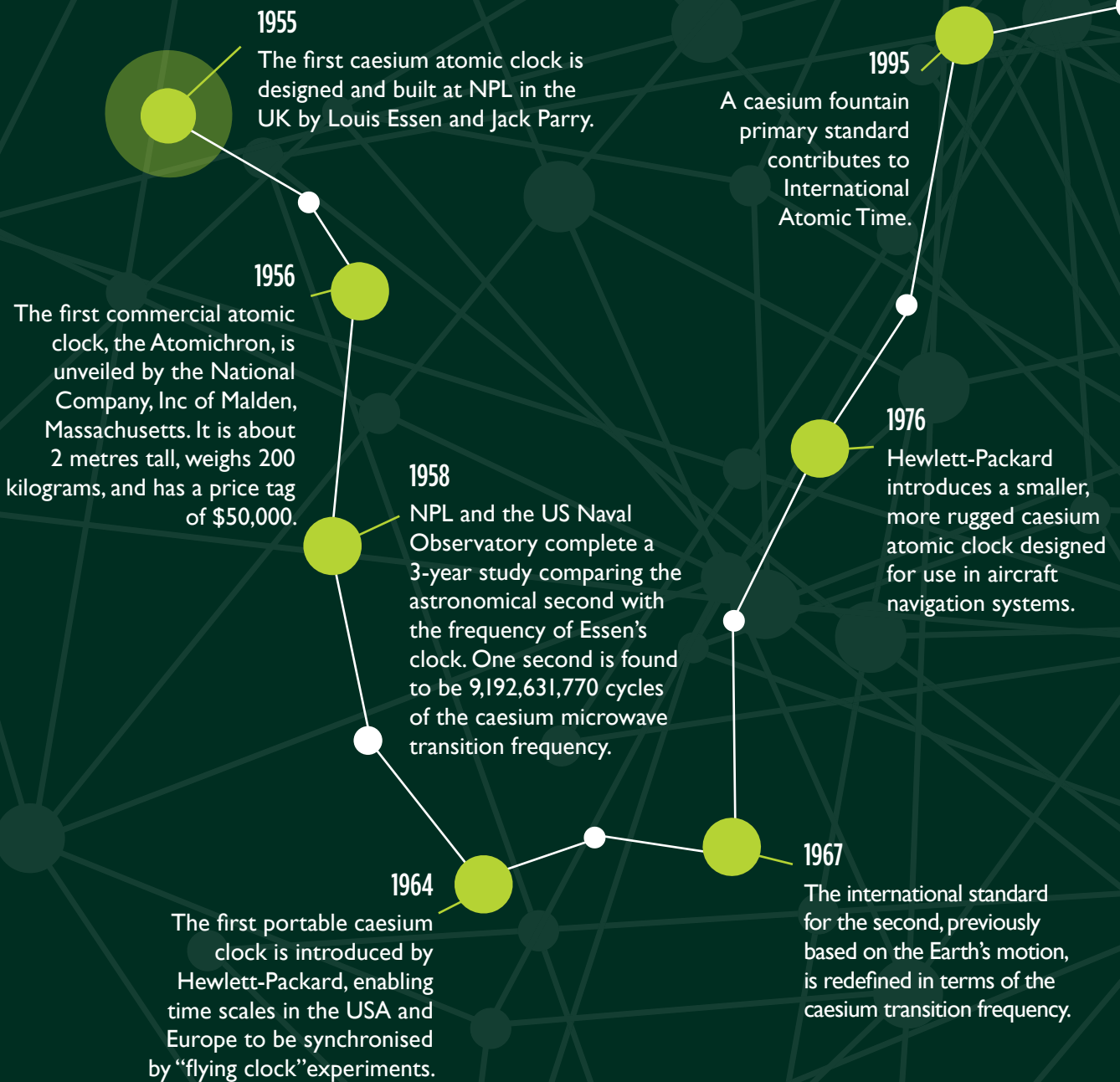
Sea level is not the same everywhere on Earth, and different countries use different benchmarks against which to measure heights above sea level. This can lead to embarrassing and costly mistakes in engineering projects.

During the construction of the Hochrhein bridge, straddling the river Rhine between Germany and Switzerland, it became clear that one end of the bridge was 54 cm higher than the other. Germany measures height relative to a benchmark in Amsterdam on the North Sea, while Switzerland uses the French reference point in Marseille, on the Mediterranean sea. There is a 27 cm difference between these two versions of sea level. The engineers applied a correction for this known height difference – but with the wrong sign. It may appear to be a trivial error in the end, but it highlights the need for international standards to avoid these problems completely.

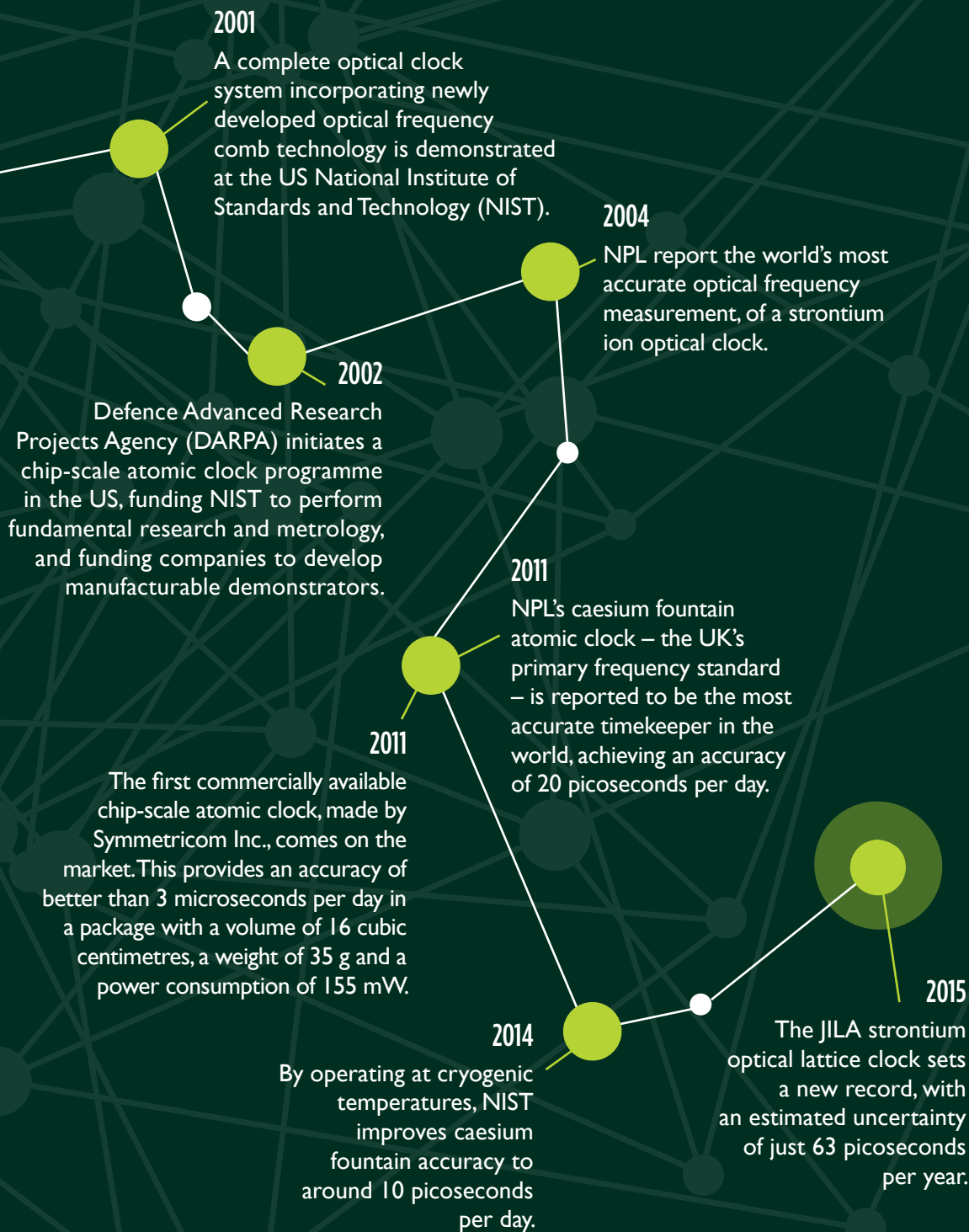
Optical atomic clocks offer a new approach called relativistic or clock-based geodesy, whereby the different national height systems could be unified. The rate at which a clock ticks depends on the gravity potential it experiences: for example, clocks closer to the Earth's surface run more slowly than those further away. The difference is only a few nanoseconds per year for two clocks a metre apart in height, but the unprecedented precision of optical atomic clocks means that they could be used to measure differences in the level between different locations with an accuracy of 1 cm.



# ATOMIC CLOCKS TIMELINE









# SPACE-BASED CLOCKS,

mainly for communications and navigation satellites, will provide a large future market

NPLTime®, a fibre-based service that offers the financial sector a certified time signal independent of GNSS. Similar services are being developed in the Netherlands and the USA.

**FUNDAMENTAL SCIENCE EXPERIMENTS** will probably be among the first to benefit from clocks of higher stability. One example is the Square Kilometre Array (SKA), a global effort to build the world's largest radio telescope. Once completed, the SKA will combine data from up to a million antennae, enabling astronomers to monitor the sky with unprecedented resolution. For the telescope array to operate properly, the observations made in these diverse locations must be tightly synchronised using extremely stable local clocks.

**SUBSEA OIL EXPLORATION** needs accurate timing too. In reflection seismology, a ship launches sound waves downwards. The sound bounces off different rock layers, and a grid of sensors on the ocean floor detects these echoes. By recording the time it takes for echoes to reach each sensor, it is possible to build up a picture of the different layers of rock and sediment – and the quality of the picture depends on the precision of the timing. GNSS timing signals don't penetrate water, so quartz crystal oscillators are normally used, but they suffer from frequency drift over time as well as frequency shifts due to the temperature difference between ocean

surface and floor. Miniature atomic clocks could provide much more stable timing over wide variations in temperature.

**SPACE-BASED CLOCKS**, mainly for new communications and navigation satellites, will provide a large future market. For example, according to the European Commission, the development budget of the European GNSS system, Galileo, is €2400 million<sup>5</sup>, and accurate clocks underpin its technology. In space there is a need for stable and accurate yet small and light clocks, with low power consumption. Higher performance clocks would also have to be corrected less frequently, and could lead to improvements in positioning accuracy. Such clocks have the potential to revolutionise deep-space navigation. With stable clocks on board, a spacecraft could calculate its own timing and navigation data without a two-way link to Earth – reducing mission costs and improving capabilities for time-critical manoeuvres such as landings or flybys.

The time to reach market will be longer for space-borne clocks than for ground-based clocks, as they face additional technical challenges. These clocks must survive the extremely high forces and vibrations experienced during launch and deployment, large changes in temperature and high levels of cosmic radiation. In addition, reliability is even more important than for ground-based



applications, with no servicing possible and a need to operate without failure for many years.

**RADAR SYSTEMS** will also benefit from improved atomic clocks, which would enable more sensitive radar capable of locating smaller targets.

**COMPLETELY NEW MARKETS** could be opened up by portable atomic clocks with higher stability and accuracy. For example, they can make accurate measurements of the Earth’s gravity potential, to unify height reference systems (see Clock-based Geodesy, page 23). Long-term measurements of the gravity potential would have considerable environmental and societal impact – which could include revealing sea level shifts from climate change.

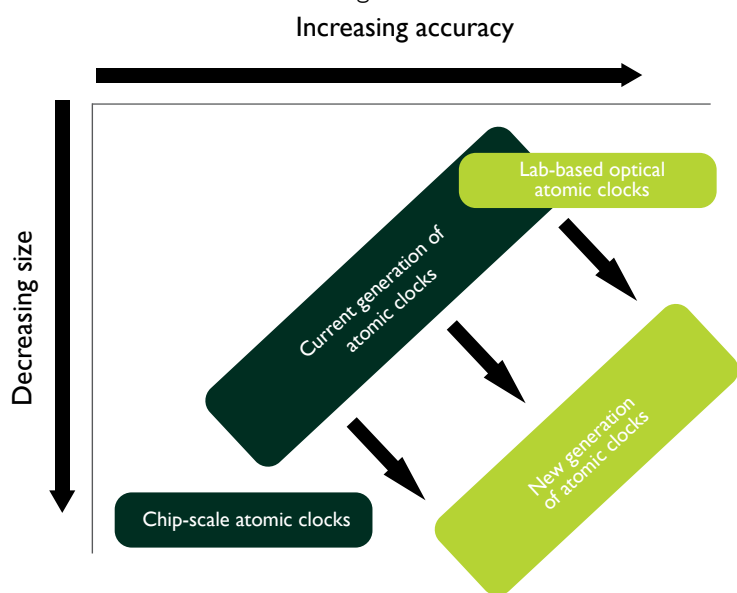


Figure 1. The trend for the development of atomic clocks. The most accurate atomic clocks are usually largest, with smaller clocks being less accurate. However, a new generation of clocks is being developed to improve accuracy whilst reducing size, weight, power consumption and cost.

### CLOCK DEVELOPMENTS IN THE UK

The atomic clocks used as the main standards for international timekeeping are room-sized and confined to a small number of national measurement labs around the world, such as the National Physical Laboratory (NPL) in the UK. A range of clocks based on these has been commercialised to tailored requirements, depending on whether reduced size, weight or power consumption is important for a particular market. However, smaller versions of these clocks are less accurate.

To address this, a new generation of atomic clocks is being developed at NPL and at other labs in the UK and around the world (see Figure 1). The UK National Quantum Technologies Programme seeks to capitalise on our research strengths in this area, in order to commercialise these new devices. The aim is to keep improving stability and accuracy, while cutting size, weight, power consumption and cost – eventually to produce miniature devices that are cheap and simple to use, and that can be integrated into current and future systems. Under this programme, a range of portable and robust clocks is being developed by the Birmingham-led Quantum Technology Hub for Sensors and Metrology, and at the NPL Quantum Metrology Institute. Any new clocks developed must be compared against national time standards to ensure they perform correctly. This can be done via a chain of comparisons with progressively higher performance clocks, with a national standard at the end of the chain.

### THE WAY FORWARD

If we are to take advantage of our leading position today, commercialisation must be properly supported – for example, by tailoring funding schemes to ensure effective collaboration with industry.

The new generation of clocks can act as holdover devices when GNSS timing goes down. To aid this development, we should review the GNSS dependency of critical services such as power, communications and banking. Government could specify how long these services should be able to operate on holdover timing.

We will also require standards to specify the performance needed for such holdover devices. Telecom operators, financial institutions, power companies and other critical service suppliers will have to show that their clocks meet the relevant standards. The UK National Quantum Technologies Programme puts the UK in an excellent position to be a leading supplier of such clocks.

Investing in an optical fibre network linking key locations around the UK would have many benefits. It would enable atomic clocks to be checked against national time standards

## Embedding atomic clocks throughout key networks is an important driver for the development of miniature, low-cost atomic clocks as part of the UK National Quantum Technologies Programme

remotely, instead of having to be moved to NPL each time, allowing problems to be identified at an early stage and reducing the time to market. Such a network could also be a test-bed for technology demonstrator experiments, not just for clocks but also quantum communications (Chapter 6). This would have to be an all-optical network, unlike existing infrastructure that mixes copper with optical fibre; and it must also provide continuous access and long-term security, unlike the National Dark Fibre Infrastructure Service which has research council funding for five years from 2014. Such a network would provide the UK with a unique resource on which to build research, innovation and high-value manufacturing.

Finally, government can help to stimulate the development of UK atomic clocks by supporting demonstrator projects, or by being a first user. As an example, Innovate UK could implement a city-scale demonstrator to show how atomic clocks can help us to develop world-leading telecommunications infrastructure.

### CONCLUSIONS

The UK squandered its scientific advantage with the earliest atomic clocks. Now a new opportunity for wealth creation is wide open. The services, research expertise and intellectual property developed at NPL and universities can be combined with UK industrial know-how in photonics, ultra-high vacuum systems and electronics. All together this puts us in an excellent position to become a leading supplier of the new generation of atomic clocks.



The UK is in an excellent position to become a

**LEADING SUPPLIER**

of the new generation of atomic clocks

CHAPTER 3:

# QUANTUM IMAGING



**\$33.4 BILLION**

global market in diagnostic imaging by 2020

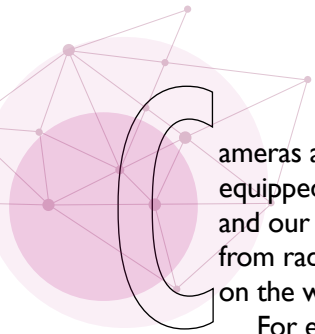
3D imaging market is estimated at  
**\$16.6 BILLION**  
by 2020

Thermal imaging predicted market of

**\$11.2 BILLION**

by 2020

Miles Padgett



Cameras and imaging are ubiquitous in the modern world. Through our phones and other devices we are all equipped to film and broadcast to the global community. But most of this imaging is restricted to visible light, and our images are two-dimensional. By contrast, the real world is three-dimensional and multi-spectral: from radio, through visible light, to gamma rays. Quantum technologies are unlocking these new windows on the world, making the invisible visible.

For example, cameras based on quantum technologies can take fully 3D images, and even identify approaching objects out of the line of sight. This could provide unique data for driverless vehicles, and have applications in many other sectors including healthcare, defence, security, transport and manufacturing.

The UK has a unique level of collaboration between academia and industry in quantum imaging. Continuing and deepening this relationship would bring many commercial opportunities.

### WHAT IS QUANTUM IMAGING?

Exploiting quantum mechanics has enabled us to make cameras that both surpass the performance of the previous state-of-the-art, and provide new forms of imaging not hitherto possible. There are two broad types of technology:

- devices that measure single photons, such as a single photon avalanche detector (SPAD). 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 don't work
- systems that use quantum effects to get around limitations in detecting light. These can make sharper images than non-quantum

cameras, and reduce noise below what once seemed to be a fundamental limit.

However, not all imaging involves the detection of light. We can image underground features by mapping the tiny changes in gravity from place to place – revealing oil reserves, sinkholes and other buried objects such as gas and water pipes (see Chapter 4).

### MARKET AREAS

One of the biggest markets for quantum technologies may be medical imaging. X-ray machines are common throughout the clinical world today, but they involve exposing patients to ionising radiation. Cameras based on quantum technology may at some point in the near future provide optical images of features

1. A laser is directed at a point on the ground beyond the corner. The light then scatters back off the ground in all directions.

2. The object around the corner is illuminated with the laser light which is scattering off the ground. This light is then scattered back off the object, some of which reaches the ground within the camera's field of view.

3. Some of the light scattered off the object is then further scattered off the ground and arrives at the camera, where it is detected.

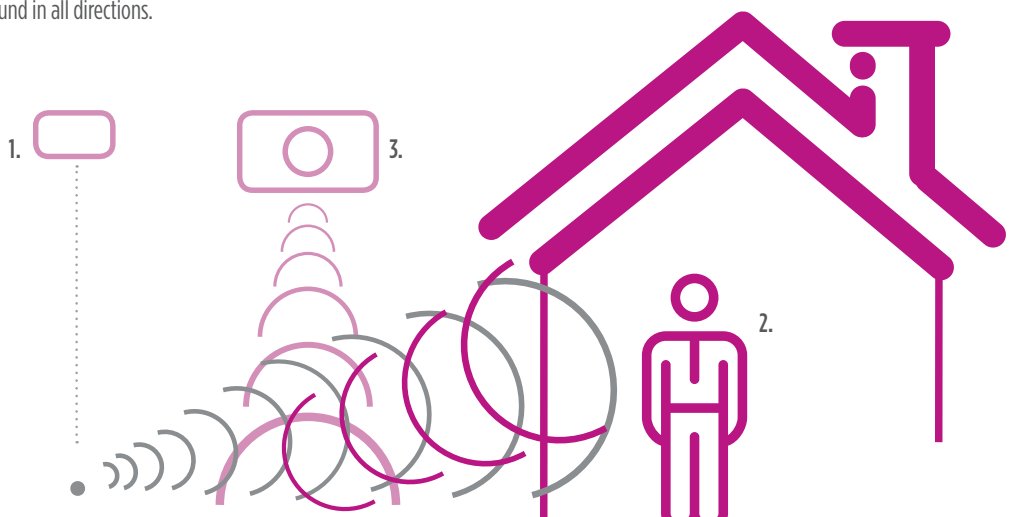


Figure 1: This system can be used to work out where an object currently is around a corner, tracking and predicting the object's movement in real time. The height and width of the object can also be determined.

within the body, mimicking X-rays without the radiation dose. One study projects a global market in diagnostic imaging of \$33.4 billion by 2020<sup>1</sup>.

Imaging in the infrared has many applications. For example, it can allow firefighters to see through smoke and engineers to image gas leaks (see *Gas Sight*, page 35), and will be widely used in surveillance. Thermal imaging alone is predicted to have a market of \$11.2 billion by 2022<sup>2</sup>.

There will also be countless uses for cameras able to image directly in 3D. By 2020 the 3D imaging market is estimated at \$16.6 billion<sup>3</sup>.

There will also be big markets for quantum imaging in low-light surveillance and microscopy. Airborne quantum imagers may be used in security, military, agricultural, oil and gas and environmental monitoring applications. Military applications include covert range finding, while the ability to image under water, through cloudy or murky environments and beyond the line of sight will find both military and civilian uses. Quantum technology will also enable cheap and effective gravity mapping of underground features for civil engineering, oil exploration and hazard awareness. Quantum imaging could also increase the bandwidth of quantum secure communication systems.

## WHAT QUANTUM IMAGERS CAN DO

### SEE IN 3D

A camera based on SPADs can measure the arrival time of individual photons. Using a pulsed illumination source, photons travelling from source to object can be timed, and this information can be used to measure depth. Adding depth perception to the normal 2D image allows imaging in 3D. For eye safety you can't use too bright an illumination pulse, so this approach needs a camera that can detect single photons.

Paradoxically, some of the most promising new cameras for 3D imaging are based on just a single-pixel detector<sup>4</sup>. These single-pixel detectors can also be used to measure the arrival time of a single photon and so take 3D images<sup>5</sup>. They have the advantage of being much cheaper than multi-million pixel cameras, and could act as sensors for autonomous vehicles.

### SEE AROUND CORNERS

Being able to know what's hidden around a corner or behind a wall could provide a crucial advantage in many situations, from collision avoidance to search and rescue (see *What's Inside That Building?*, below). SPAD arrays can do this too.

Figure 1 shows how this technique works. A pulsed laser illuminates a spot on the floor some distance ahead of the camera. Light is scattered from this spot and hits the hidden object, bouncing off it back into the field of view of the camera, and finally a little of this light is scattered again to the camera. The unprecedented single-photon sensitivity means that this faint triple-scattered light can be detected – and used to calculate the position, size and speed of the hidden object or objects<sup>6</sup>. Even recovering an image of the object may be possible, although it requires more computational power than is yet available.

### SEE IN THE DARK

Traditional infrared cameras that have millions of pixels are very expensive. This is another area where single-pixel quantum imagers will be cost-effective – as will a new class of detectors that operate efficiently in the near infrared, which can be manufactured using established and inexpensive processes for making consumer digital cameras. These new detectors can also form integrated on-chip sensors for use in telecoms.

## WHAT'S INSIDE THAT BUILDING?

Dstl's Centre for Defence Enterprise is funding a collaboration between academia and Thales to understand the design criteria for an imaging system that can see around corners.

Such systems have already been demonstrated over distances of a few tens of metres, and are able to look several metres around a corner. However, for most applications, it will be necessary to achieve detection at greater distances. This project will determine the feasibility of using a novel approach to improve performance over 100 metres.

# QUANTUM IMAGING TIMELINE



**1969**

Bell Labs conceives design of charged couple device (CCD), the basis of digital imaging for many decades.

**1980**

Politecnico di Milano demonstrates millionth of second timing resolution for a single-photon avalanche diode detector, enabling photon time of flight (range to object) measurements.

**1995**

University of Maryland demonstrates quantum ghost imaging based on the use of an entangled down conversion source, allowing images to be formed from light that has “spookily” never seen the object.

**2000s**

Industry produces electron multiplying CCD camera offering unprecedented photon sensitivity and hence ultra-low light imaging in a compact camera format.



2002

University of Rochester draws parallels between quantum and classical ghost imaging, enabling ghost imaging to be performed with a conventional light source.

2008

Rice University builds a single-pixel camera incorporating compressive sampling to replace focal plane array, bringing low-cost imaging to a wavelength where traditional cameras don't exist.

2010

Istituto Nazionale di Ricerca Meteorologica shows experimental realisation of sub-shot noise quantum imaging, and hence low-light imaging without the noise.

2011

Andor, Hamamatsu and others demonstrate sensitivity of scientific CMOS rivals EMCCD, bringing ultra low-light imaging to scientific and consumer products.

2014

University of Vienna demonstrates quantum imaging using undetected photons, removing the need for detectors at challenging wavelengths.

2014

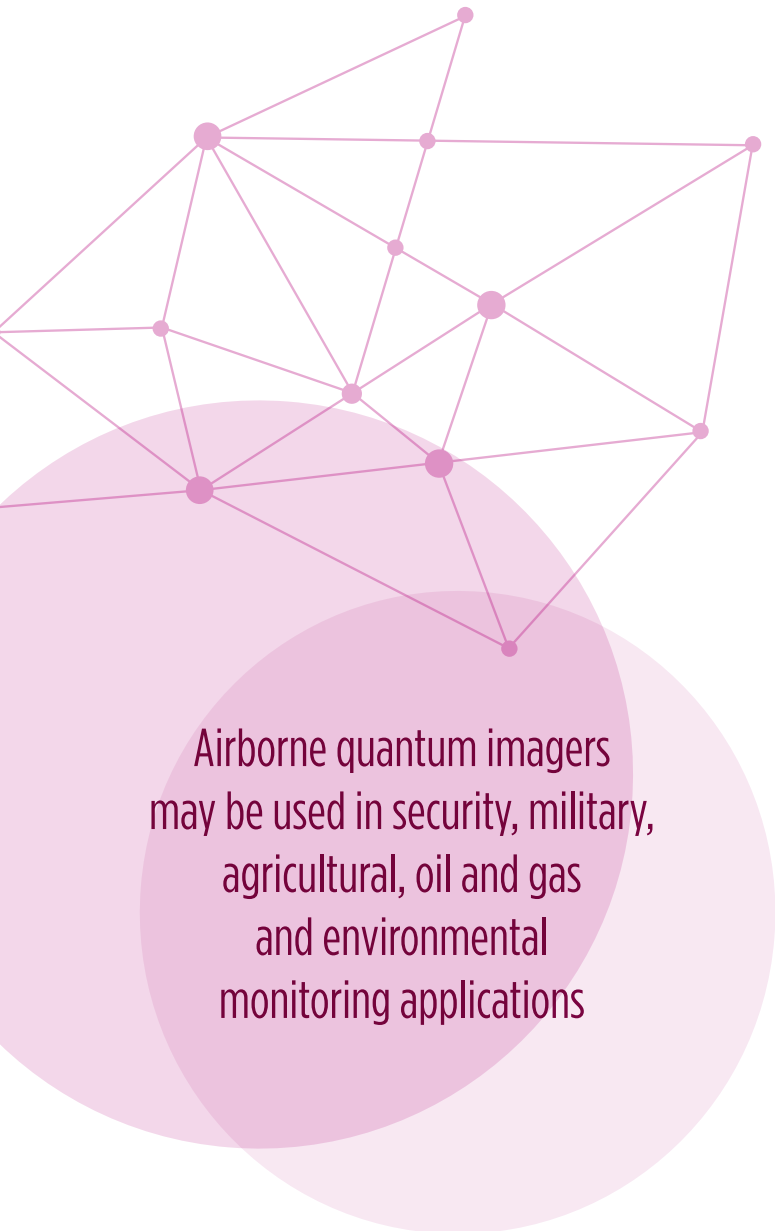
MIT demonstrates first-photon, low-flux imaging of 3D objects, where the light level is so low that the average number photons is less than one per pixel.

Forecast 2018

Low-cost, single-pixel cameras used for visualising gas leaks.

Forecast 2020

High sensitivity cameras used to track objects out of the line of sight for applications in autonomous vehicles.



Airborne quantum imagers may be used in security, military, agricultural, oil and gas and environmental monitoring applications

#### SEE CLEARLY

Imaging invariably suffers from noise. Even lasers, the purest source of light commonly used for optical measurements, have various sources of noise, including “shot noise” – the random fluctuations caused by the fact that light is made of individual particles called photons. Although seemingly an insurmountable barrier, shot noise can be overcome using quantum technologies.

Some types of crystal can split a laser beam into two beams of quantum entangled photons, with correlated properties. This means that the noise is identical on the two beams, so dividing the number of photons measured in one beam by the number of photons measured in the other yields a ratio that is noise free. A slight change in intensity in one beam appears as a change in this ratio and can be detected even in the presence of shot noise<sup>7</sup>.

Another way to get a high quality image from

#### LED BY LED

LEDs are now commonly used in lighting rooms. The QuantIC imaging hub is developing ultrafast LED illumination capable of projecting high-frequency patterns. Undetectable to the human eye, these patterns can be used to send information to devices around the room – indicating their position and directing them to undertake tasks.

The hub has worked with industry on developing the new technology, and is now seeking to advance demonstrator projects in collaboration with other commercial partners to explore possible applications.

noisy data is using an algorithm to clean it up, based on both the raw data and the known properties of images. When the number of photons involved is very small, shot noise has unique characteristics that image de-noising algorithms can exploit<sup>8</sup>.

#### GHOST IMAGING

A conventional camera relies on capturing light that comes back from an illuminated object or scene – the wavelengths of the illuminating and captured light are the same. However, quantum imaging allows illumination of the object with infrared light, but collection of the image using visible light.

Starting with a UV laser, a crystal splits this light into visible and infrared beams (see Figure 2). While the infrared beam illuminates an object, the visible beam hits the camera. By

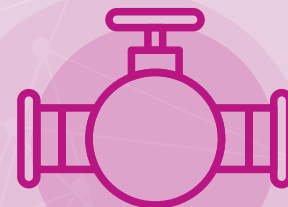
exploiting the relationship between the beams (technically known as entanglement – see Chapter 1) the camera can build up an image of the object. As a result we can use a conventional high specification visible camera that is much more sensitive than its infrared equivalent<sup>9</sup>.

This idea works for analysing the chemical composition of samples too. A sample can be tested using light of one wavelength, while recording is done using another wavelength where measurement systems are more sensitive<sup>10</sup>.

**SEE WITHOUT BEING SEEN**

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. 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 the ranging of objects with ultra-low intensity light, undetectable by anyone else.

**GAS SIGHT**



Gas sensing is used in the oil and gas industries, building and construction, food processing, healthcare and water treatment. The global gas sensing market was estimated at \$1.78 billion in 2013, and there is a gap in the market for a cheap, small, low-power and highly portable remote gas detection system.

A project led by M Squared Lasers Ltd is investigating the capabilities of a prototype single-pixel camera: a portable system for detecting methane leaks. The system detects the absorption of infrared light by the methane and produces an image of the methane cloud. The prototype camera has already demonstrated promising performance and a follow-up project is now under way to increase the sensitivity of the system and boost its range to 5 metres.

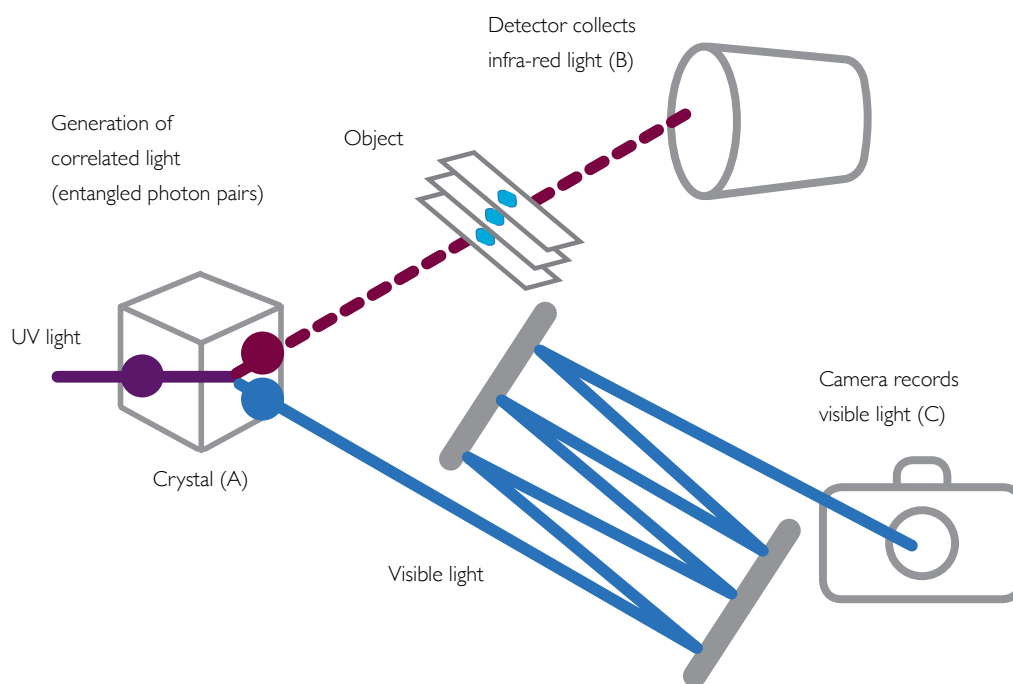


Figure 2. **Ghost Imaging.** This setup allows the illumination of an object using hard-to-detect invisible wavelengths (infra-red) and yet form an image using a camera which detects visible light. A crystal (A) splits UV light into infra-red and visible light (in the form of entangled photon pairs). The photons in each pair are correlated, meaning that there is an intrinsic link between them even though they are separated, and move further apart. The infra-red light illuminates an object, and the light that makes it through to the other side is detected by the infra-red detector (B). The image is formed from the second photon in the pair being recorded by the camera (C) at a visible wavelength.

**THE WAY FORWARD**

The UK has unique connections between the academic and industrial communities involved in quantum imaging. These connections range from the structure and membership of the various advisory boards, to the delivery mechanisms embedded within quantum technology hubs (such as partnership resource funds and joint calls with Innovate UK), to the various UK hubs' focus on making technology demonstrators.

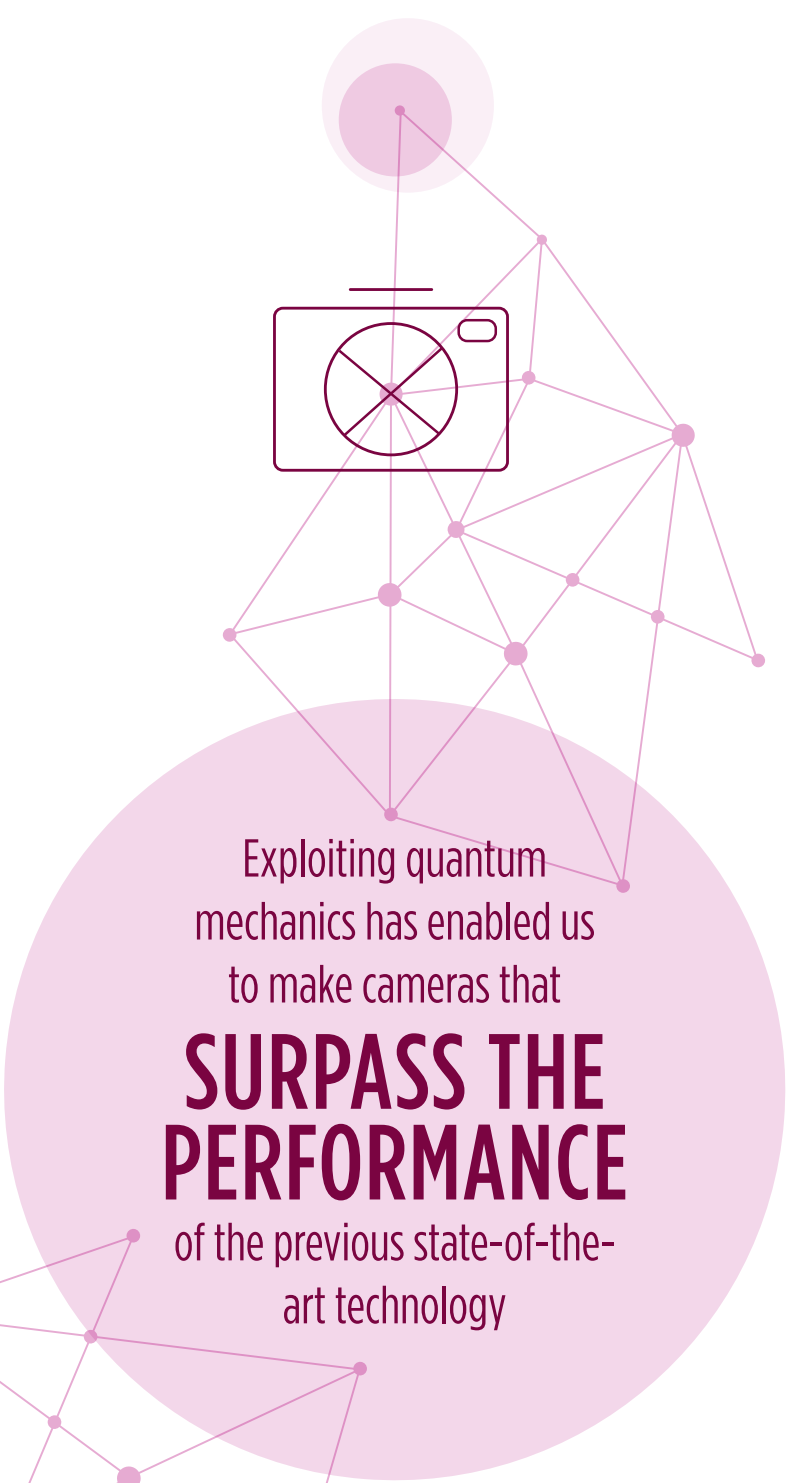
While these connections are already paying off – the QuantIC hub is co-running 16 imaging projects with industry, for example – we need to maintain a focus on technology translation into new products and services for UK-based industries to exploit. Future investment should concentrate on areas where the UK has a track record of taking real products to market.

Continuation of the hub network will strengthen this focus and lead to deeper industrial engagement. Rather than being solely academic operations, the hubs could be transformed into joint academic and industrial centres. They could mimic the Catapult or other types of innovation centres that are based around academic and industrial partnerships. The future of the quantum hub network should be closely aligned with the new-look Innovate UK, with longer-term opportunities funded through focused UK Research and Innovation (UKRI) schemes and programmes.

**CONCLUSIONS**

Imaging is among the most well-developed fields within the second quantum revolution, and the abilities of quantum imaging to transcend conventional cameras will lead to myriad applications. Some of these are already being pursued by collaborations through the UK National Quantum Technologies Programme, but to truly take advantage of the industrial opportunities we would benefit from an extension and strengthening of the hub network.

# Imaging is among the most well-developed fields within the second quantum revolution



## CHAPTER 4:

# QUANTUM SENSING AND MEASUREMENT



Quantum sensors promise to turn gravity mapping into a key enabler of modern civil engineering

The UK sensors and instrumentation industry contributes

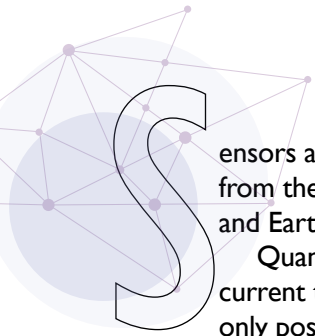
**£14BILLION**

a year to the economy

**73,000**

people are employed by the UK sensors and instrumentation industry

Kai Bongs  
Miles Padgett



Sensors are used in everyday technologies to detect motion, sound, light and many other things. They range from the billions of low-cost motion sensors in mobile phones to high-end, high-value systems in healthcare and Earth observation.

Quantum sensors can offer a step change in performance: more sensitive, accurate and stable than current technology, sometimes by many orders of magnitude. They can unlock new applications that are only possible with such improvements – feeding into high-performance markets and sectors including aerospace, climate, construction, defence, energy, healthcare, security, transport and water.

Some quantum sensors are already being commercialised. The UK can benefit from manufacturing high-end sensors. Further opportunities will be found in the ecosystems of services that develop around these devices, from engineering and surveying firms to data interpretation and visualisation.

### HOW DO QUANTUM SENSORS WORK?

Some quantum sensors use atoms to sense changes. This works because the atoms can be controlled and measured precisely. In quantum physics, particles such as atoms can act like waves, exploring extended areas of space. They can be put in two places or two states at once. Because this quantum superposition is highly sensitive to the environment, it can be used as the basis for precise sensors.

For example, in an atom interferometer atoms are trapped as a tiny cloud. The cloud is then released and falls, with precisely-timed laser pulses used to control it as it goes. The atoms behave as waves, which interfere with one another like ripples crossing on the surface of water. The pattern made by this interference depends on what is influencing them as they go. If that's simply falling under gravity, it allows for very precise gravity sensing (see Mapping Gravity, page 42).

Alternative types of quantum sensor make use of atoms embedded in materials such as diamond and silicon. These are particularly suited for magnetic sensors. Other devices use photons, the particles of light. For example, photonic sensors can detect the optical properties of molecules to measure faint chemical traces. We can also use quantum technology to improve the read-out of classical devices such as MEMS (micro-electromechanical sensors) technology (also see Mapping Gravity).

We can make quantum sensors to measure acceleration, gravity, rotation, time, pressure, temperature and electric and magnetic fields. In future, even more effective sensors could be based on the delicate phenomenon of quantum entanglement.

### MARKET AREAS

The UK sensors and instrumentation industry employs 73,000 people, contributing £14 billion a year to the economy.<sup>1</sup> Services based on sensor data generate much more value, so it is important to consider the entire value chain.

Quantum magnetic sensors may reduce the cost of magnetic brain imaging, allowing much more widespread use. Quantum sensors for measuring gravity promise to turn underground mapping surveys into a standard tool for civil engineering. Where satellite navigation is inaccessible, quantum sensors can step in to provide inertial navigation.

#### CIVIL ENGINEERING

Underground surveys can be costly and time-consuming, but are often essential when building new infrastructure. This includes developments on brownfield sites, high speed rail, nuclear power stations and wherever the ground conditions are unknown. The underground environment presents hazards such as sewers, mineshafts and sinkholes. Having incomplete information can lead to costly delays, overruns and re-planning. Maintaining underground infrastructure is also a challenge: the UK spends around £5 billion each year to dig 4 million holes in the road<sup>2</sup>, mainly because people don't know where existing infrastructure is.

Ideally, surveys would be non-invasive: conducted above ground without the need to dig trial pits. Existing scanning techniques such as ground penetrating radar, electrical conductivity measurements and magnetometry are limited in depth and resolution, and anything more than a few metres under the ground is practically inaccessible.

Gravity sensing can provide a solution. Whatever is buried underground creates tiny variations in local gravity, so a sensitive measuring

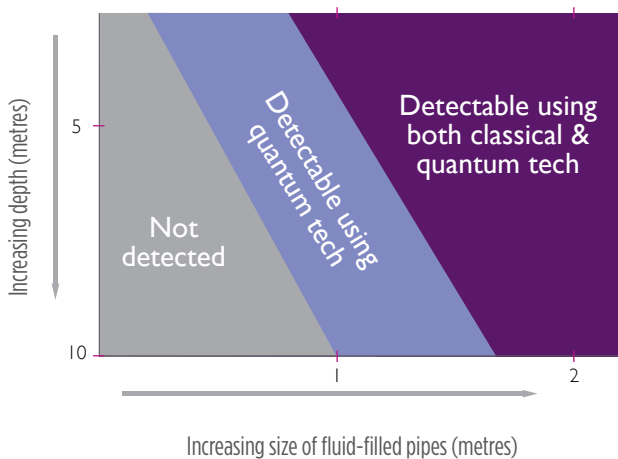
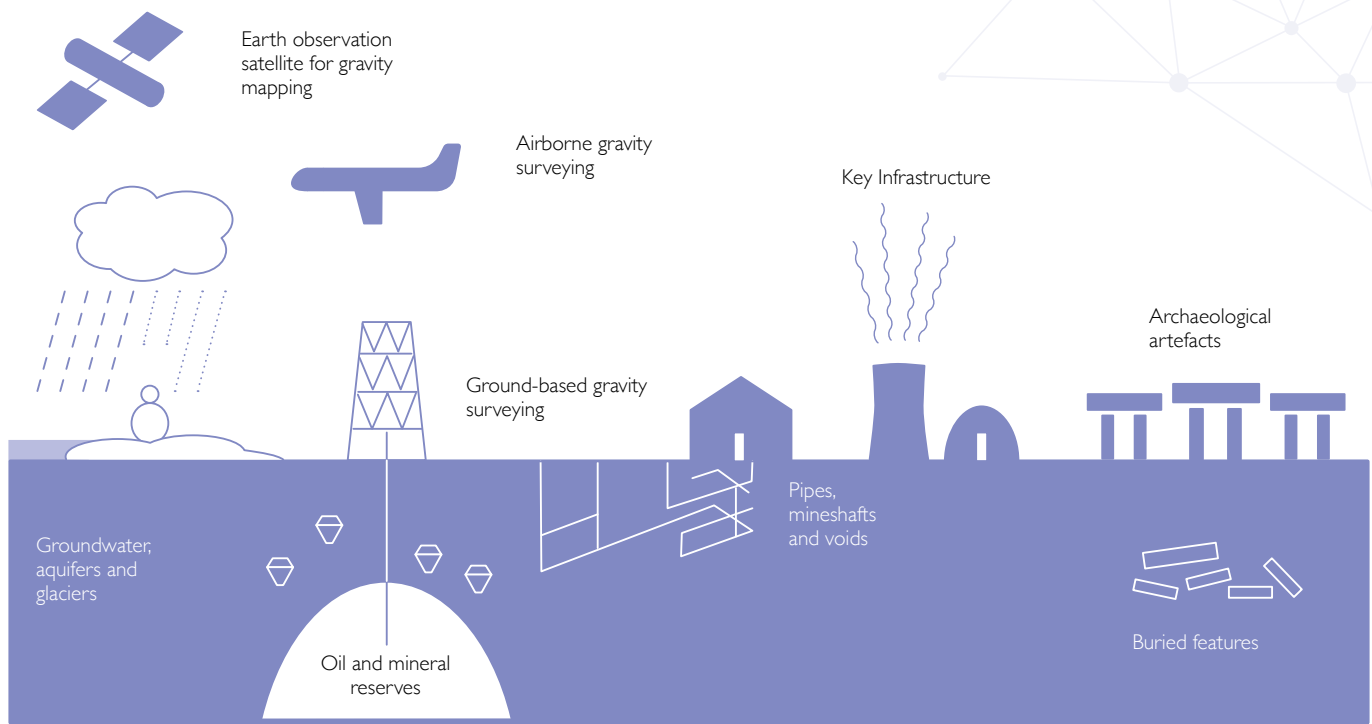


Figure 1. Above: The landscape for gravity surveying with quantum sensors.

Left: Industry is interested in detecting smaller and more deeply buried objects such as pipes. As shown, quantum technology offers this capability though increased sensitivity. These quantum sensors also offer increased measurement speed over current technology.

device can be used to make a gravity map. Although gravimeters are commercially available, existing instruments are prone to ground vibrations and the readings can drift. They are also time-consuming to use, and can confuse features at the surface with those deeper underground.

Quantum sensors for measuring gravity should offer many advantages over this conventional technology, such as being faster; more precise and able to see deeper. They can subtract outside effects, such as ground vibrations. They may also offer a hundredfold speedup in the mapping process. As well as promising to be a key enabler of modern civil engineering, quantum sensors for gravity are set to have an impact on other sectors. Figure 1 shows the landscape for prospective applications.

#### NATURAL HAZARD PREVENTION

More than 5 million UK homes are in high risk zones for sinkholes and subsidence; while UK

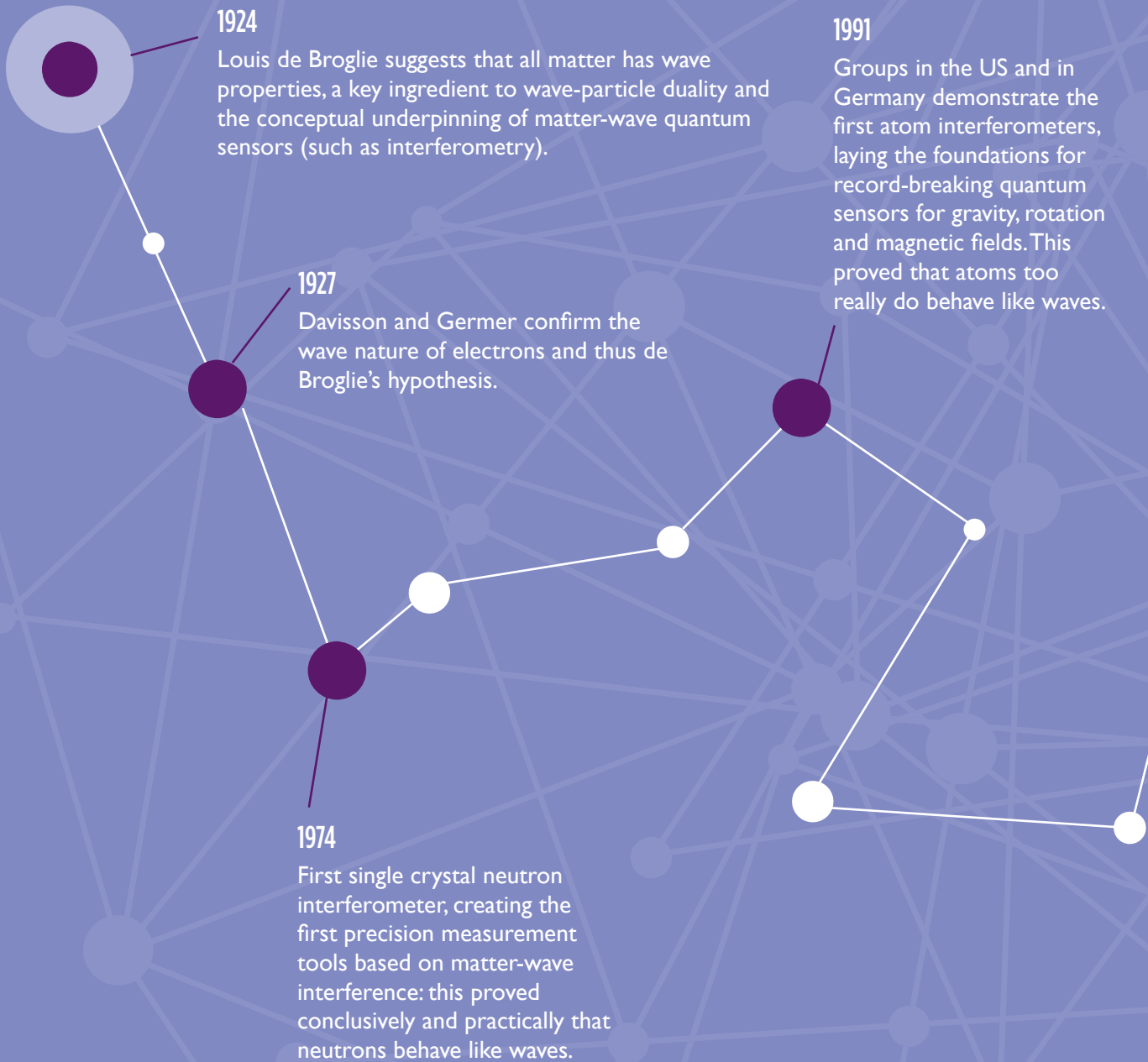
rail infrastructure needs continuous monitoring for water accumulation in the track bed, which increases the risk of landslips. Sinkholes have lower density than surrounding ground, while water saturation creates higher density. Both anomalies could be identified on gravity maps provided by quantum sensors. Such devices can enable faster mapping, so routine scanning would be feasible. For example, putting sensors on trains could provide a regular, automatic assessment of rail tracks.

In addition, quantum photonic sensors will quickly and easily identify chemical hazards in the ground, such as oil leaking from buried tanks.

#### NATURAL RESOURCE EXPLORATION

Accessing natural resources such as oil and gas relies on knowing where to drill. Currently the exploration market is dominated by seismic surveys, a market worth \$3 billion in the US in 2015<sup>3</sup>. Gravity surveys are only carried out where more detailed information is needed, because they are even more expensive – but much of their cost comes from the time needed to level out the measuring devices. Quantum-enhanced MEMS sensors (see Mapping Gravity, page 42) remove or reduce the need for levelling, allowing faster surveys at potentially less than a tenth of the cost.

# QUANTUM SENSORS TIMELINE





1997

The Nobel Prize in Physics is awarded to the development of laser cooling methods for atoms, allowing the preparation of atoms as near-ideal probe particles. This meant that we could exploit the wave nature of atoms to make extremely useful and precise sensors.

2010

The Stanford spin-off AOSense delivers the first commercial atom interferometer gravity sensor: the first real matter-wave product arrived.

2011

An atom interferometer is flown on a plane, demonstrating the ability to measure inertial effects on a moving platform – providing a proof of concept towards practical inertial navigation using atom interferometry.

2012

A team from NIST uses a Chip Scale Atomic Magnetometer to measure brain waves: this new class of device opens a new chapter in the study of brain activity.

2012

The European Space Agency recognises cold atom devices (optical clocks and atom interferometers) as crucial future technology and subsequently initiates technology development programmes for cold atom quantum technology sensors in space.

2013

The ability to create robust stand-alone quantum sensors is demonstrated by dropping a functional interferometer from height to mimic microgravity (as experienced in space). This raises the realistic prospect that these precise sensors could be used in real-life systems in moving and aerospace platforms.

2016

Potential five-fold advantages of optical atomic magnetometer in magnetoencephalography (MEG) demonstrated, opening up the way for research towards novel diagnostic tools for brain diseases such as schizophrenia or dementia.



**TRANSPORT AND NAVIGATION**

Transport increasingly relies on accurate knowledge of a vehicle’s position and the conditions of the road or track. This is reflected in the spread of satellite navigation and the number of radar, ultrasound, optical and other sensors on cars, trains and aeroplanes.

However, modern developments are posing new challenges for sensor technology. Positioning and route navigation for autonomous vehicles and trains will require a precision of 10 centimetres; next-generation driving assistance systems will have to monitor road conditions for local hazards at the centimetre level, but from

smaller objects on runways. Using quantum sensors based on cold atoms, a navigation system can calculate position to centimetre accuracy. They also work where satellite navigation fails or is unreliable: underwater, underground, in tunnels and in densely built environments.

Meanwhile other types of quantum sensor (operating in the terahertz waveband) will be able to assess roads to millimetre level. Also, new laser-based microwave sources, originally developed for atomic clocks, promise airfield radar systems with greater range and higher precision.

**MAPPING GRAVITY**

Not all imaging involves the detection of light. One powerful new form of imaging is to map the tiny changes in gravity from place to place – revealing, for example, troublesome old mine shafts, sinkholes and other buried objects such as gas and water pipes. At a different scale and range, gravitational variations can help to identify new oil reserves and mineral deposits, as well as mapping and monitoring the water table.

New gravitational sensors exploiting quantum cold atoms (atom interferometers) and quantum-enhanced MEMS (micro-electromechanical sensor) technology have much higher performance than previous devices, and should capture previously unreachable and commercially important applications<sup>4</sup>.

Low-cost MEMS devices can now be envisaged, about the size of a tennis ball, which are similar to but a million times more sensitive than the silicon motion sensors used in smartphones. These could be inexpensive enough to scatter over a large area, to give a full image of the gravity field.

Quantum imaging can provide an advantage in reading out MEMS sensors, providing orders of magnitude sensitivity gain. Researchers at Glasgow University and Bridgeporth have developed a sensor, the Wee-g detector, and are now improving it by using

quantum light sources to cut noise, so that even smaller masses can be detected – potentially finding people buried in avalanche or earthquake debris.

Cold-atom sensors will have the highest levels of precision, to reveal for example the smallest of old mine workings in a cost effective and time efficient way, which is not possible using today’s techniques. A cold-atom sensor is now being developed by the University of Birmingham, RSK and e2v which is expected to enable everyday use of gravity surveys. This could give the construction industry certainty of what’s under the ground, reducing delays due to unexpected hazards and removing the need for expensive exploratory excavation.

In space, cold atom sensors promise to enable new discoveries through the detection of gravitational waves and by testing some of Einstein’s theories. By sensing gravity precisely, this technology can also be used for Earth observation from space, enabling the mapping of groundwater reserves as well as monitoring changes to glaciers and ice caps<sup>5</sup>. At the University of Glasgow and Clydespace, researchers are aiming to create a transformative new space-based technology, using MEMS sensors to miniaturize spacecraft altitude control, improving the capabilities of nanosatellite technology where the UK has a strong industrial position.



## Quantum magnetometers can offer higher sensitivity with less infrastructure, promising to make certain types of healthcare screening more cost-effective

### HEALTHCARE

**DEMENTIA.** According to the Alzheimer's Society, the annual cost of dementia to the world economy is more than £500 billion, and growing<sup>6</sup>. Today diagnosis is based on a patient questionnaire, which often only indicates the disease when there is so much damage that treatment options are severely constrained. Earlier diagnosis and intervention could result in better outcomes<sup>7</sup>.

A type of brain scan called magnetoencephalography (MEG) is being investigated by researchers to assist with earlier diagnosis. However, the technology currently requires a magnetically shielded room and liquid helium cooling, making screening of the population unfeasibly expensive. Quantum magnetometers can offer higher sensitivity, do not require such cooling and need less shielding, promising to make this technique more cost-effective. They work by using the magnetic properties of atoms as sensitive probes.

**CANCER.** An imaging technique called microwave tomography has already been investigated for the early detection of breast cancer<sup>8</sup>. Quantum sensors

could help to improve the sensitivity and resolution of such techniques. Unlike X-ray mammography, microwave imaging does not involve exposing the breast to ionising radiation.

In addition, diamond-based quantum sensors have made it possible to study the temperature and magnetic field inside living cells down to the atomic level, providing a new tool for medical research.

**HEART DISEASE.** Cardiac arrhythmias are a big cause of death in rich countries. They are characterised by an irregular, slow or accelerated heartbeat. Magnetic induction tomography is being developed as a tool to diagnose fibrillations and investigate their causes and mechanisms. This method can be vastly improved with quantum magnetometers. With such a boost this technology has the potential for bedside imaging, leading to much easier screening and monitoring of patients, and improved surgery planning and navigation.

## THE WAY FORWARD

Lab experiments have already demonstrated quantum sensors for gravity, rotation, and electric and magnetic fields with a sensitivity exceeding that of conventional technology. We are now working to make them more robust, portable and compact.

To translate these fundamental results into economic benefit, we need to:

- transfer knowledge between academia and industry
- enable a commercial supply chain and build market confidence by demonstrating how quantum sensors can solve real-world challenges.

These are the aims of the UK National Quantum Technologies Programme. The programme has already been successful at pushing fundamental research results towards technologies with an impact on the economy. However, given the disruptive nature of many potential applications, there is uncertainty over market figures and many companies are hesitant to invest in full product development. So now it is time to move the quantum technologies programme towards a challenge-led approach that helps to connect with the interests of these companies.

The UK should set up innovation centres to trial quantum sensors and undertake applied development. These facilities would provide fertile ground for developing quantum-based services, growing a commercial ecosystem that is deep rooted in the local region. They could train engineers in using and integrating these new technologies, so they can engage with end users and markets, and would understand and respond to their challenges. These centres would add clustering of service and end user areas on top of the existing clustering of quantum scientists and engineers in the current hub structures.

To facilitate innovation, we should also take a flexible and long term approach to regulation. For example, the application of Eurocodes building regulations could require thousands of boreholes for ground inspection in the development of the High Speed 2 rail link between London and Birmingham. Under more flexible regulations the need for costly boreholes could be reduced or replaced by geophysical surveying techniques. This would

reduce costs and give quantum sensor providers a new market. Other examples are healthcare and autonomous vehicles, where it is important to ensure safety but at the same time allow innovative approaches. UK regulators are already adapting regulations to allow innovations in the future, but they could do more by engaging earlier with innovation roadmaps and adapting regulations to foster interactions between innovators and markets.

Finally, launching competitions for public technology demonstrator programmes would incentivise companies to be the first in the market – putting them at the forefront of the international competition and able to harness most of the economic benefit. These projects could be chosen to fulfil strategic national needs. Good examples are the quantum navigator and quantum imager for gravity commissioned by the Ministry of Defence, via the UK National Quantum Technologies Programme. These have already triggered interest from the US, China and Europe. Similar programmes could be launched for the railway and road networks, in the healthcare sector, and for flooding, groundwater monitoring and natural disaster prediction.


## CONCLUSIONS

The spread of quantum sensors promises to enhance our competitiveness and reduce costs. Mapping underground UK will bring insights and commercial benefits. There will be opportunities to manufacture high-end sensors and develop service industries around the stream of data that ensues – opportunities that could be grasped with the help of innovation centres, technology competitions and the right approach to regulation.

**The UK should set up innovation centres to trial quantum sensors and undertake applied development**

## CHAPTER 5:

# QUANTUM COMPUTING AND SIMULATION

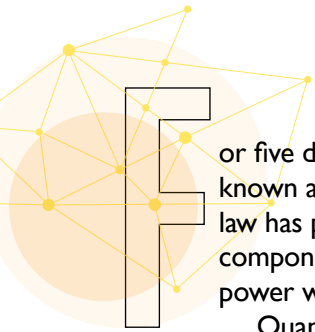


Quantum computers operate in a fundamentally different way, using the rules that govern the atomic scale

The need for ever more processing power has sparked a **WORLDWIDE** race to build a quantum computer

The UK is taking a lead in both the hardware and software of quantum computing

Myungshik Kim  
Muffy Calder  
Derwen Hinds  
Dominic O'Brien



or five decades, the number of transistors on a silicon chip has been doubling every two years, a trend known as Moore’s law. Today a chip can hold billions of transistors, each about 100 atoms across. Moore’s law has powered the explosion in computing power and IT. But this trend can’t go on forever, because components are approaching a fundamental limit in size: that of the single atom. Conventional computing power will probably grow much more slowly as we approach this limit.

Quantum computers offer a way forward, because they operate in a fundamentally different way, taking advantage of the rules that govern the atomic scale. They have the potential to be much faster than conventional supercomputers for certain tasks, including some of great commercial significance. Full-size quantum computers, while currently a long way off, could aid aircraft design, data search, city management and medical diagnostics, among many other things. The UK is taking a lead in both the hardware and software of quantum computing needed to reach that goal.

**HOW QUANTUM COMPUTERS WORK**

These devices exploit the complex nature of quantum information. While a conventional computer uses bits, with values of zero or one, a quantum computer uses qubits. Each qubit can be zero, one, or both (see Figure 1). In other words it can be put into a quantum superposition: a simultaneous combination that could be, say, 75% zero and 25% one.

Because qubits can be put into many states at once, a quantum computer can process many inputs simultaneously instead of having to go through them one by one like a conventional machine. For some types of problem, this can mean a much faster solution.

- quantum dots (small semiconductor devices) and diamond nanoparticles. These are at an earlier stage, but are being pursued by many institutions worldwide.

**WHAT QUANTUM COMPUTERS CAN DO**

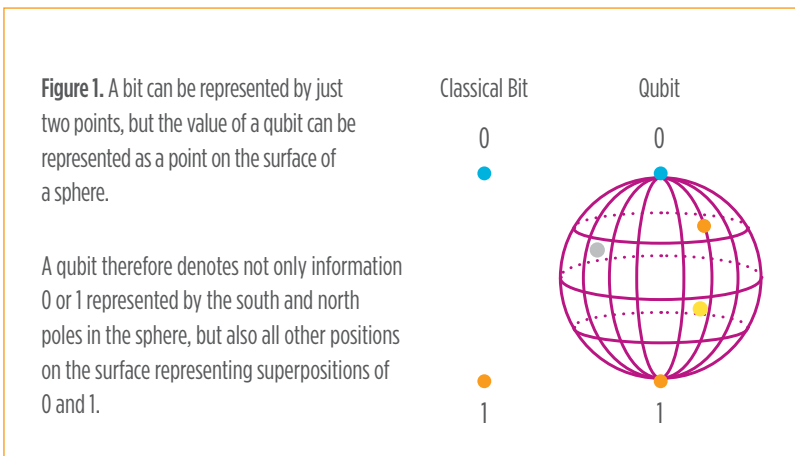
We already know of a few problems where a quantum computer should beat conventional computing, including searching large databases and factoring large numbers (see Two Quantum Algorithms, page 48).

Factoring is of critical importance because it is behind the most common form of cryptography, which is used to protect financial and other sensitive data. A large enough quantum computer could easily break this kind of cryptography, and we should prepare for that “crypto-apocalypse” (see Chapter 6).

There is also evidence that a quantum computer should beat conventional machines for certain optimisation tasks. A huge range of commercial activities rely on optimisation – for example, cars and planes are optimised using computer models before any real parts are manufactured. Aircraft wing design is an especially complicated case, where quantum computing may offer more efficient designs and ultimately better aircraft. Major aerospace firms are interested in quantum computing for this reason.

We are now looking for algorithms that give a quantum speedup in other areas, including machine learning and scenario planning. Machine learning is increasingly used for tasks such as voice or facial recognition, image recognition for robots and autonomous vehicles, as well as decision-making.

A growing need for scenario planning comes from smart city initiatives, where huge amounts



Qubits can be realised and manipulated using several different technologies.

- superconductors. Superconductor-based qubits are being developed by several large IT companies
- photons. The UK has highly developed activity in this area (see Computing with Photons, opposite page)
- trapped ions. The UK is leading some aspects of this technology

of data are gathered. Increased computing power could help us make better decisions in real time. Scenario planning is also valuable in medical diagnosis, defence, finance, and many areas of commerce.

All of these tasks will require a large quantum computer, but there are other problems where a smaller machine with 50 to 100 qubits is of value, including the design of new materials, drugs and other molecules. Small quantum computers called quantum simulators are arrays of interacting qubits that can simulate another quantum system – providing an insight into physical processes that are very difficult to model today. Proof-of-principle quantum simulators already exist, and UK institutions have taken a lead in photonic simulators (see Computing with Photons).

### QUANTUM PROGRAMMING

Once we are able to build full-scale quantum computers we will not only want new algorithms, we will need entirely new programming languages. This will require new techniques for program specification (the definition of what a program should do), verification (proof that the program does what we want), debugging and testing. Debugging and testing are especially challenging, because quantum states are affected by being observed – so when you check what is happening in the computer, you change it. Designing systems to catch errors when the program is compiled could be one solution.

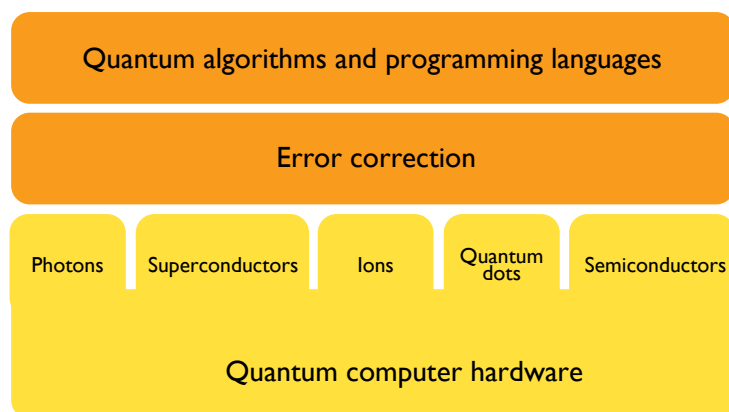


Figure 2. The overall architecture for a functioning quantum computer. There are various possible options for the type of hardware. Information processing can introduce errors into the results, so error correction is typically needed. Finally, we need specialised algorithms and programming languages.

## COMPUTING WITH PHOTONS

UK research teams are among the world leaders in developing photonics for quantum computing.

This method uses:

- sources of single photons in pure quantum states (the qubits)
- optical circuits to perform logic operations with these photons
- memories to store qubits
- photon detectors to read out the result of a computation.

Versions of these components have been developed by UK researchers, in collaboration with others across the globe. Oxford and Bristol are leading the development of technology to generate photons at a high rate and to create programmable photonic circuits, while Toshiba Research Laboratories in Cambridge has pioneered semiconductor light sources.

Southampton University is leading the fabrication of integrated optical circuits, also known as waveguide chips. Several kinds of memory are being developed by UK groups.

Photonics may provide the first unequivocal demonstration of supremacy in quantum computing. At Oxford and Bristol, small photonic simulators are leading the race to show quantum speedup in statistical sampling<sup>1</sup>.

There is active research in developing quantum algorithms and programming at various universities across the UK.

### THE RACE TO BUILD A QUANTUM COMPUTER

Within a decade we will probably have quantum computers with 50 to 100 qubits, which will already be useful as quantum simulators. The goal in the longer term is to build a large-scale computer that can run any quantum algorithm: a universal quantum computer. To outperform conventional computers, these will require many thousands to millions of qubits.

The UK is well placed in this race, thanks to the National Quantum Technologies Programme and other investments, but we face competition from government-funded programmes in the Netherlands, US, Singapore, China, Australia and elsewhere.

There is also strong commercial interest, especially in small-scale quantum simulators. For example, a Canadian company, D-Wave, has developed two types of quantum simulator, and several have been installed in large companies and a US national institute, although it is not yet established that they show quantum speedup.

Google, IBM and Intel have also launched programmes to build quantum simulators and full-size quantum computers using superconductor-based qubits. These efforts are spawning a growing number of start-up companies, with a broad range of quantum information processing expertise.

### THE WAY FORWARD

The National Quantum Technologies Programme is focused on building and supporting a pipeline from basic physics to products: physicists studying new phenomena and devices; engineers in academia improving performance and reliability at a small scale; transfer of the technology into commercial R&D labs; prototypes and testing; production and sales.

The government can help by maintaining long-term funding and support at all stages in this process, including training of researchers and engineers, infrastructure, research and technology development. In particular, it is important to provide a coherent training environment to bring together physical and computer scientists and engineers.

Government is not subject to the same near-term commercial constraints as private sector organisations. This gives it a unique ability to act as a demonstration client. Demonstrations can focus on problems that, if solved by a quantum computer, would have real benefits to the country. Government could also use its leverage as a large customer to encourage computing services providers to engage with quantum computing research efforts.

### CONCLUSION

Success in developing a quantum computer would revolutionise information technology, with huge commercial implications. The UK already has a lead in some forms of quantum computing, and with the right environment we can benefit from developing the devices, exploiting their power and running the new quantum IT services that will follow.

## TWO QUANTUM ALGORITHMS

*Shor's algorithm* is a fast way to find the prime factors of large numbers with a quantum computer. This is important because public-key cryptography rests on the fact that multiplying large numbers together is straightforward for a conventional computer, but the reverse is not. When provided with a large number, even today's supercomputers find it difficult to work out its prime factors – the prime numbers that multiply together to give that answer. With a quantum computer, this would no longer be true: factoring would be no harder than multiplying. Factoring a 1,024-bit number would be enough to break most existing public-key cryptography, such as internet payment systems. That would probably require a machine with tens of thousands to a million qubits<sup>2</sup>.

*Grover's algorithm* is a fast way to search a database with a quantum computer. Imagine a phonebook, organised alphabetically. If you know the name and you want to find the number, you can easily look it up; but if you know the number, and want to find out whose number it is, you just have to start looking through entries one by one. On average, you will have to search through half the phone book before you find it. A phonebook with a million names would present the wearying prospect of checking half a million entries. But using Grover's algorithm with a quantum computer, on average you would only have to check a number of entries that scales with the square root of the total number. Now if there are a million entries in total, that means one thousand, rather than half a million.

Within a decade we will probably have quantum computers with

**50 TO 100 QUBITS**



CHAPTER 6:

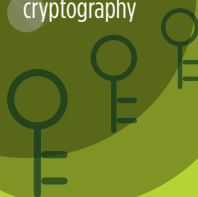
# QUANTUM COMMUNICATIONS

**PQC and QKD**

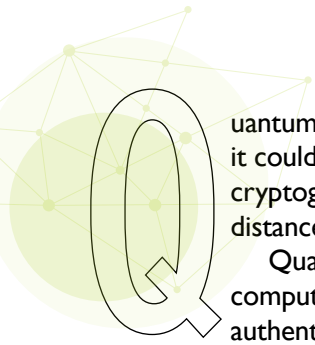
are important tools for  
future data  
transport security

Quantum cryptography  
is based on a communication  
system in which information is  
encoded in quantum states

Perhaps the  
most important application of  
quantum communication will be  
cryptography



Andrew Lord  
Erika Andersson  
Derwen Hinds  
Kenny Paterson  
Andrew Shields  
Tim Spiller



Quantum communications will provide very high security for transmitting sensitive data. In the near term it could be used to supply the secret keys and random numbers that are an essential resource for cryptography; eventually it could be used in a secure global communication network operating over long distance fibre and satellite links.

Quantum communications could also be used to transport information in a large scale quantum computer, to generate truly random number sequences for simulation and gaming, and to ensure the authenticity of documents more securely than existing digital signatures.

### A CRYPTIC PROBLEM

Perhaps the most important application of quantum communication will be in cryptography. Cryptography is built into every web browser and mobile phone, and underpins secure communication in our networked society. Cryptographic keys, analogous to keys in the physical world, are used to encrypt data at one end and decrypt it at the other.

For most online commerce and other secure communications on the internet, we use public key cryptography<sup>1</sup>. Each user sets up two keys – a public one that other people can use to encrypt data, and a private one for the user to decrypt it. The two keys are mathematically related, but as long as a hacker can't work out the private key from the public one, the whole method is secure\*.

One popular algorithm for public key cryptography uses large numbers as the public key, and their prime factors as the private key. It is currently safe because working out the prime factors of a large number is hard to do even with supercomputers. But a large-scale quantum computer could do that calculation easily (see Chapter 5). This would have such serious consequences that it is sometimes called the crypto-apocalypse.

There are two promising options to replace existing cryptographic systems: quantum key distribution (QKD) and post-quantum cryptography (PQC).

### QUANTUM KEY DISTRIBUTION

This method distributes secret keys in a way that cannot be effectively intercepted, because through quantum mechanics their secrecy can be tested and guaranteed (see How QKD Works, page 52).

This process is based on fundamental principles of physics, so it should not be possible

to break quantum cryptography by future advances in computing or mathematics.

QKD has some limitations. It can only be used over optical fibre or along a line-of-sight laser beam, not on copper wire or mobile communications. Although most long-distance communication is over fibre, the last stage of transmission to users tends to use mobile technology or copper wire.

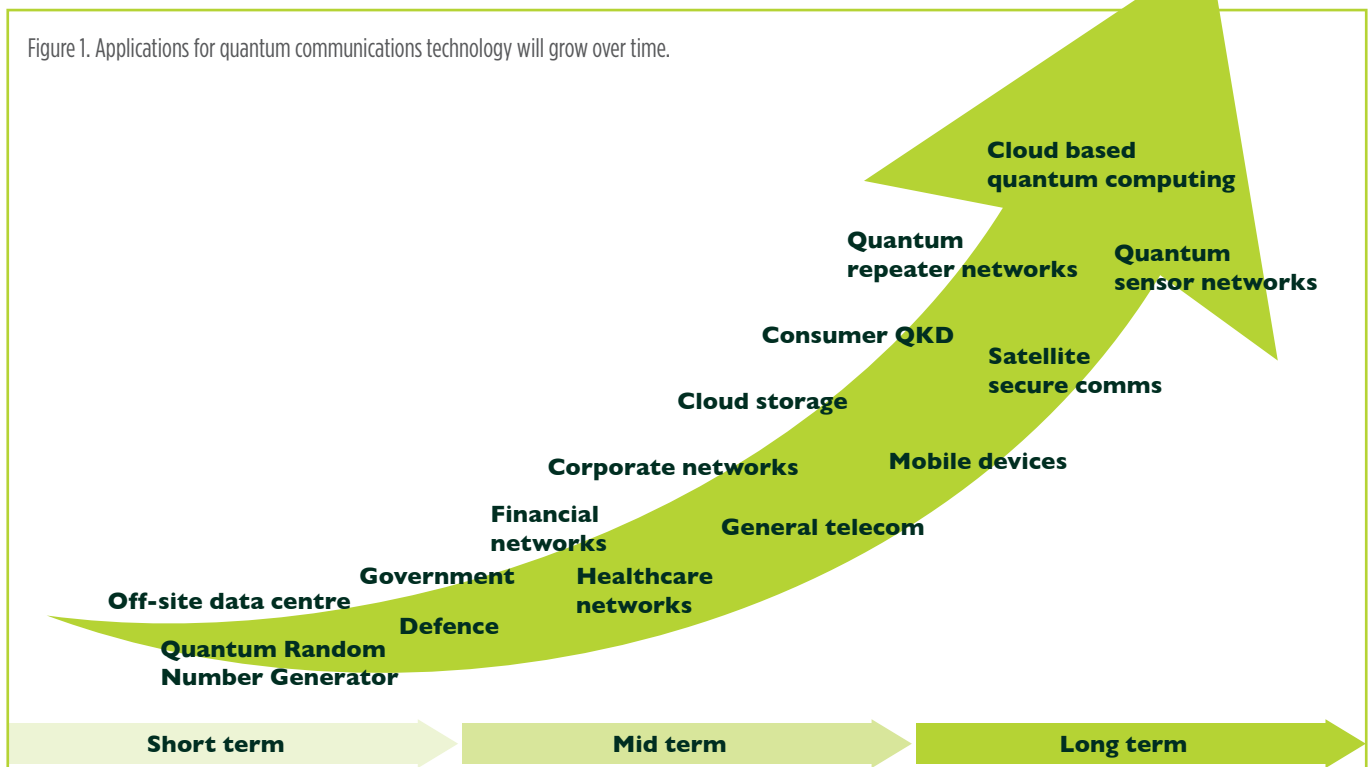
The range of QKD is currently limited in practice to about 100 km over optical fibre, as beyond this too many photons are absorbed or scattered. This distance can be extended by building a quantum network, which at present requires trusted nodes – essentially locked rooms or equipment racks where keys are exchanged automatically. In future, networks with full quantum security should be possible (see Quantum Networks).

To ensure the theoretical promises are achieved in practice, care should be taken over the implementation of QKD systems, including initial authentication of sender and receiver.

## There are two promising options to replace existing cryptographic systems: quantum key distribution (QKD) and post-quantum cryptography (PQC)

\* Because this process is slow, it is not used to encrypt large volumes of data, but instead to encrypt another key that can then be shared between sender and receiver. This third key is then used to encrypt and decrypt the data.

Figure 1. Applications for quantum communications technology will grow over time.



### WHAT QKD CAN DO

A promising early application for quantum cryptography is to secure data that must remain secret for several years, such as sensitive information about critical infrastructure, commercial secrets or personal medical and financial data. Although existing cryptography is difficult to break with current computers, communications recorded today could be cracked by hackers in the future with more powerful computers or better analytical techniques. In contrast, data encrypted using quantum cryptography should not be vulnerable to any form of technological development. So one company in Japan has introduced a service using quantum cryptography to encrypt genome sequence data, which people will want to keep secret for their lifetimes and even those of their descendants.

QKD can be integrated into a fibre optic communications system and used to secure the entire data payload. This could be used to secure traffic between a company, bank or hospital and an off-site data centre, where confidentiality is at a premium given the large volume of sensitive corporate and personal information. As the cost of the technology falls, we can expect ever greater penetration into communication networks. QKD may also be

used to secure the telecom infrastructure itself, preventing hackers from taking control of large portions of the network.

Given the parallels with conventional laser-based communication technology, quantum communications will probably get cheaper quickly and may become a standard component in network hardware, tapping a huge potential market.

QKD should be especially suitable for:

- financial and customer data storage by large institutions. Banks are already trialling or considering proof-of-concept demonstrations of QKD
- back-up of health records, including human genome data
- government and military communications
- security of national infrastructure, including telecoms and power plants.

### POST-QUANTUM CRYPTOGRAPHY

Post-quantum cryptography (PQC) is quite distinct from quantum cryptography. Rather than exploiting the quantum properties of physical systems, PQC employs cryptographic algorithms that are believed to be secure to the threat posed by quantum computing.

Government, academia, industry and standards bodies are working to develop these algorithms<sup>2</sup>. The community is currently investigating a range of proposals for the next generation of quantum resistant algorithms, with several leading contenders including lattice-based cryptography. Google is already trialling another PQC algorithm (called ring-learning with errors) in its Chrome browser<sup>3</sup>.

All PQC proposals have pros and cons that usually involve a trade-off between key size and computational efficiency. Different approaches will be more or less suited to different scenarios.

Standards organisations such as NIST and ETSI will consider how to compare the effective security of these approaches, to advise cryptography policy. It will take time to reach a consensus on which proposals are most appropriate for different applications, and to move away from current approaches, as many communications protocols will have to change to accommodate PQC.

PQC and QKD are important tools for future data transport security and both are being

actively researched<sup>4</sup>. It is important that both PQC and QKD approaches to security should continue to be investigated in parallel. Eventually they may even be employed together as a double lock on security.

**THE POWER OF QUANTUM COMMUNICATION**

While cryptography is the most discussed application, quantum communication should have many other uses, (see Figure 1) including:

**QUANTUM SIGNATURES**

Encryption alone does not guarantee that a message cannot be altered by an adversary, so

**It is important that both PQC and QKD approaches to security should continue to be researched in parallel**

**HOW QKD WORKS**

Quantum cryptography is based on a communication system in which information is encoded in quantum states, usually the states of a single photon. Quantum theory ensures that if a hacker attempts to intercept and read the quantum data stream, the encoding of the single photons will inevitably be altered. This can be detected as errors in the system, raising an alert that the communication is not secret.

In QKD, this is used to send digital keys that can then be used to encrypt data (see Figure 2). If a would-be hacker steals some of the photons, those photons are simply not used to form a key because they don't arrive at the receiver. A hacker can try instead to measure the state of each photon, and resend a copy to the receiver, but this does not work because it is impossible to precisely determine the state of even a single photon, no matter what advanced technology is used. The hacker can only ever obtain partial information and will have to guess the rest. This results in detectable errors for the sender and the receiver.

Once the key is established at both ends, it can be used to encrypt and decrypt data in just the same way as before. QKD provides a secure way to distribute the keys in the first place – and it can generate keys rapidly, allowing regular refreshing of new keys to encrypt the data.

digital signatures are used today in contracts, email and financial transactions. They show that messages are not tampered with, and are authentic. Quantum signatures are in some respects similar to currently used public-key signatures, and could offer better security.

**POSITION-BASED TAGGING**

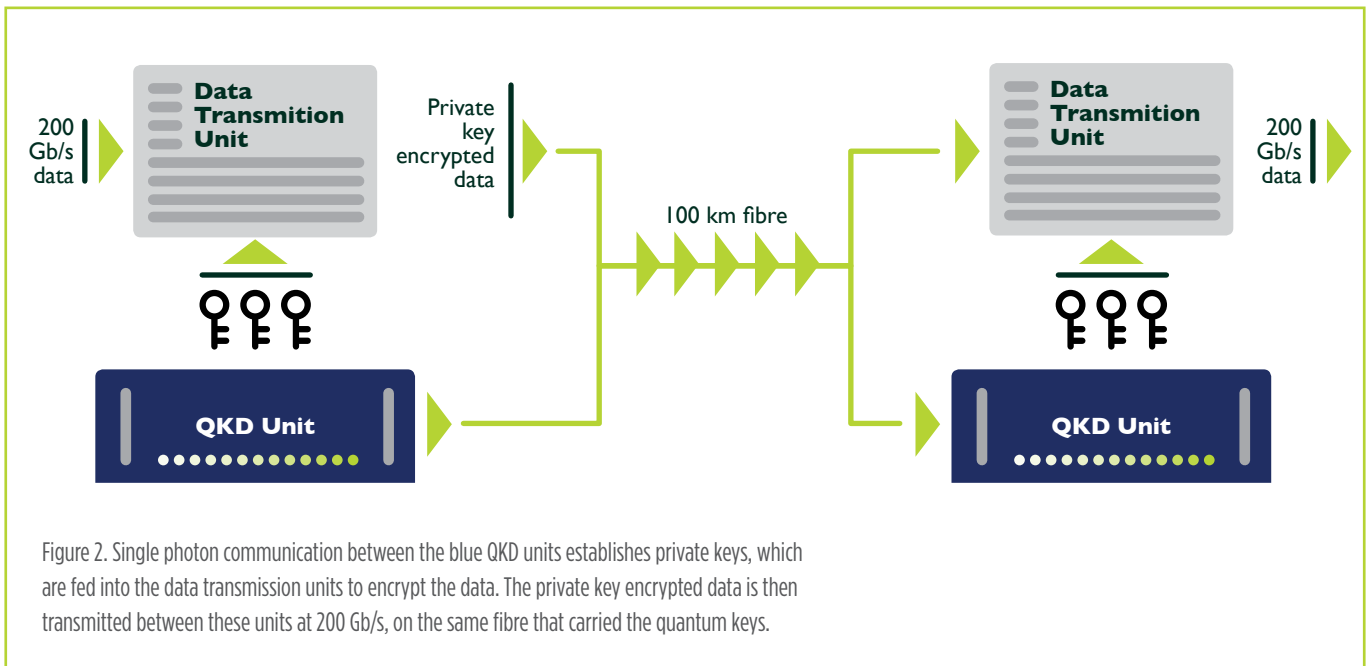
This is used to authenticate the location of a valuable or important device. We are now investigating how this can be improved by quantum means.

**QUANTUM COMPUTING**

One way to make a large quantum computer may be by interconnecting many small quantum processors through quantum communications, perhaps based on entanglement.

**RANDOM NUMBERS**

These are a vital resource for cryptography, gaming and numerical simulations. All these applications are affected by the quality of the randomness available. What are known as pseudorandom number generators based on computer algorithms are not truly random, and even numbers gathered from measuring noise in a physical device show some



predictability. Cryptography can be compromised by such predictability, and there are documented reports of attacks on cryptosystems exploiting weaknesses of the random number generator.

Quantum processes are inherently unpredictable and can therefore produce truly random numbers. For example, it is impossible to guess whether a photon will be reflected or transmitted by a half-silvered mirror, which can be used to generate a single random bit. The creation of photons by a laser can be used to generate billions of random bits per second<sup>5</sup>. This and other quantum phenomena can generate near-perfect random bit sequences, and devices to exploit them have the potential to be mass manufactured cheaply. The range of applications is very diverse and includes secure cloud data storage and processing, authentication for access to the Internet of Things, mobile and fibre communications systems, computer gaming, lotteries and systems for predicting the stock market or the weather.

**FROM QUANTUM LINKS TO QUANTUM NETWORKS**

Today QKD is used in bespoke point-to-point services, generally a single stretch of optical fibre. For this to evolve towards a mainstream technology, we will need to tie QKD links together.

At present we can only do this using trusted nodes. These house several QKD systems in a closed environment with restricted

access, where keys are converted to classical information to be transferred between systems. The Quantum Communications Hub is building a national-scale QKD research network between trusted nodes in Cambridge, Bristol, UCL, NPL and BT's research centre at Adastral Park. The EU has publicised its ambition for a QKD network connecting major European cities.

In principle, a hacker might gain access to a trusted node to intercept data at a stage where it is not protected by QKD; or secure networks might be required where no nodes can be trusted. So we are now exploring how to make fully quantum-secure networks, using the phenomenon of entanglement.



With shared quantum entanglement, the sender and receiver share information that is fundamentally inaccessible to anyone else.

This concept underpins quantum repeaters, devices that enable a distant sender and receiver to share entanglement across many nodes. Research has demonstrated component features required for a quantum repeater, and we now need to synthesise these into a fully operational device.

Entanglement is also used in a new approach called measurement-device-independent (MDI) QKD. This addresses a risk with QKD, in which a hacker shines his own light signals towards the sender and receiver in order to hack in to the system. Conventional QKD systems can be designed to counteract this risk, but MDI-QKD avoids it inherently by removing the detectors at the ends and performing measurements at an intermediate node instead.

We are also researching switches to dynamically route quantum signals over paths in complicated networks. These quantum routers together with repeaters would enable distant quantum computers to communicate, creating a distributed quantum processor – and such networking could eventually lead to a quantum internet.

Satellites should be within range of quantum communication now that the required accurate alignment technology is available. The Chinese Micius satellite, launched in August 2016, is already testing the use of entanglement from space. Basic QKD links would require the satellite to be trusted by all the ground-based senders and receivers that communicate with it. However, the provision of entangled sources, or an MDI arrangement, could remove even this constraint and allow long-distance quantum communications via untrusted satellites.

**THE WAY FORWARD**

The best solution to the impending “crypto-apocalypse” is not yet certain. We could move towards a clearer plan by engaging in joint technical developments related to the two main options: QKD and PQC. That would mean more collaborative work between UK quantum communications and cryptography research groups, which would also help progress on signatures and authentication.

Our efforts in quantum cryptography would be boosted by a pilot trial of QKD,

**We need to reassure end users that these technologies will work. A partnership of the key organisations could be formed to perform conformance tests and issue accreditation certificates**

using realistic data in a realistic environment. As well as demonstrating the potential use of this technology, this would stimulate the supply chain and show UK leadership in secure communications.

We also need to reassure end users that these technologies will work. A key partnership between the National Physical Laboratory, the National Cyber Security Centre and academia could be formed, in order to perform conformance and penetration tests, and issue accreditation certificates. These partners would need to engage with other interested parties, such as stakeholders from the communications and financial services sectors. This coordinated effort would help quantum communications mature into a fully-fledged industry.

**CONCLUSIONS**

Quantum communication technologies offer the potential for very high data security, which could protect the UK’s industrial and government networks in future, as well as other applications such as quantum signatures and distributed quantum computing. Our strong research pedigree is now feeding into industry in the form of world-first proof-of-concept demonstrators – showing that the UK is still holding on to its leading position.



# CHAPTER 7: COMMERCIALISATION

**£270M**

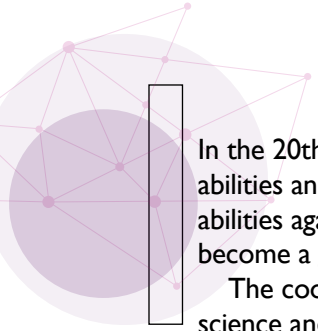
invested by the UK  
over 5 years

Quantum technology  
is set to become a

**GLOBAL**  
industry

Quantum technologies require a  
new workforce, with special skills  
and expertise

Trevor Cross  
Roger McKinlay  
Richard Murray  
Andrew Shields



In the 20th century, our microscopic control of technology led to a whole raft of previously unimaginable abilities and devices, including the entire electronics industry. Now quantum technology is giving us new abilities again. We can only see the small beginnings of this process today, but quantum technology is set to become a global industry as commonplace as today's electronics.

The coordinated programme in the UK is already making the most of our academic strength but the science and technology innovations need to be turned into industrial opportunities. The UK National Quantum Technologies Programme aims to anchor innovation in the UK with an alliance of academia, business and government.

**THE OPPORTUNITY**

Quantum technologies can bring many benefits to the UK, through the sale of components and systems, and through the use of these new devices in a huge range of industries and applications.

The UK electronics industry today is a sector with revenues of £16 billion, growing at 4.5% per year<sup>1</sup>. If quantum technologies lead to just a 5% growth of this industry over five years, that would already be £1 billion. In the longer term the impact is expected to be much larger than that and quantum technology could become comparable to the consumer electronics manufacturing sector which is today worth £240 billion a year worldwide<sup>1</sup>. Figure 1 shows some of the relevant target markets.

The emerging market for the sale of quantum devices is ripe for new entrants. Quantum technologies are different enough from existing

electronic and photonic devices that companies do not currently possess the infrastructure to guarantee a stake in the future industry. The UK has a head start, with great strength in the academic and research base, as well as in a large number of world-class and highly flexible companies with the right skills and capabilities to take early prototypes through to commercial production. This is reflected in the UK's global ranking (see Figure 2).

Our strengths in high-value manufacturing will mean UK companies are well placed to produce devices in the early life of the technology – and perhaps beyond. Due to the complexity of quantum technologies, and the time that they are expected to take to reach maturity, the UK has an opportunity to sustain a leading position in high-value parts of the supply chain.

The UK already has well-established underpinning sectors, such as photonics (see Figure 3), which can play a role in the supply chain for an emerging quantum technologies industry.

**SECTORS**



**SYSTEMS**



**COMPONENTS**

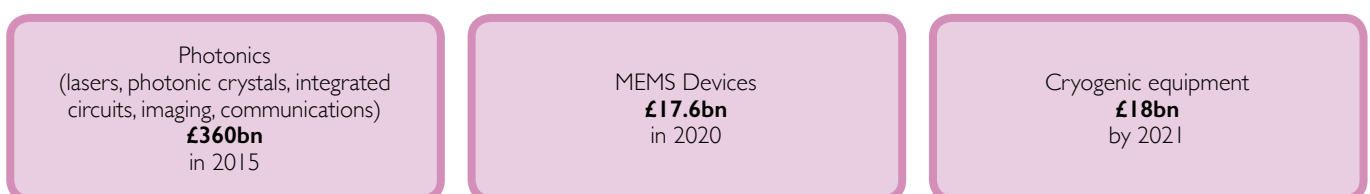


Figure 1. Quantum technologies represent a sizable opportunity for companies. This may be by selling components, integrating quantum systems, or adopting quantum technology solutions. Estimated global market sizes are provided above<sup>2</sup>. Other sizable opportunities, unknown to us right now, might also be discovered in the future.



## WHERE WE STAND

Quantum technologies are mainly at an early stage, although quantum communications and clocks are relatively mature, with some commercial products and services available. Sensors and imaging systems promise disruptive performance in a few years' time, with some pioneers already offering early products and services. Quantum computers are furthest from market, with substantial results probably more than a decade away.

Over the past five years, many governments have started to invest in programmes to exploit quantum science for wealth creation. The UK's five-year £270 million investment in 2013 was one of the earliest and remains one of the largest investments. In 2015 the university of Delft in the Netherlands, with support from Microsoft, launched a €135 million programme<sup>3</sup>. In 2016 the USA increased the size of its quantum programme and released a White House paper on coordinating its quantum technology efforts<sup>4</sup>. China is investing in a 2000-kilometre quantum communication network, and in August 2016 launched the Micius satellite, containing quantum cryptography equipment. Other large investments have been made by Singapore, Australia, Canada and Japan.

In April 2015 the UK annual spend in quantum technologies was fourth highest in the world at £61 million, with Germany, China and the USA investing £70, £127 and £208 million respectively (see Chapter 1)<sup>5</sup>.

The European Commission has funded quantum science through the Future and Emerging Technologies schemes, and recently the UK community has been working with the Commission to develop a future quantum technologies programme focused on exploitation. This will complement the UK programme, providing a chance to coordinate activities, maximise the progress of early research, fill gaps in the UK supply chain and attract talent.

## THE QUANTUM ALLIANCE

For quantum technology industries to flourish in the UK, we need academia, business and government to work together. These three key partners must form an alliance that will allow faster commercialisation: making sure that industry is involved early in the development of new technologies and that laboratories understand the needs of the market.

## ACADEMIA

The UK's world-class research in quantum technologies has been enhanced by the quantum hubs to give academics the resources, the freedom and the vision to accelerate commercialisation.

Established in 2014, the hubs have already turned quantum science experiments into early technologies and demonstrators, engaged with company partners, and helped to enhance the commercial potential of quantum technologies.

The choice of a small number of centres to develop the technology brought focus and prioritisation to the UK research landscape. In the next phase more players will become involved as research ideas mature into pilot projects and demonstrators, and industrial involvement increases. Prioritisation and coordination will become more important and more of a challenge as the number of stakeholders increases, the scale of activity grows and market opportunities mature. It is essential that the focus is maintained and the programme is actively guided forward.

	World ranking based on spend <sup>5</sup>	World ranking based on publications <sup>6</sup>	World ranking based on patent applications <sup>7</sup>	Total ranking
USA	1	2	1	1
China	2	1	2	2
Germany	3	3	6	3
United Kingdom	4	4	4	3
Japan	8	5	3	5
Canada	5	6	5	5
Australia	6	11	7	7
France	9	8	10	8
Italy	11	9	12	9
South Korea	17	10	8	10

Figure 2. Ranking of the UK in comparison to rest of world for quantum science and technology.

**BUSINESS**

To hasten quantum technologies out of the lab, academia needs to engage with business, for example by sharing knowledge through joint development projects and secondments. This ensures that the challenges associated with the later stages of development, such as marketing and manufacturing, are considered early on, and so confidence in the capability and delivery of these new technologies is established in the private sector.

In the UK, quantum technologies already have a small but growing following of companies who want to be either first to market or first adopters. To date, the hubs have received more than 150 letters of company support.

These positive sentiments must be translated into more meaningful engagement – through the investment of finance and resources – but it can be hard to get commercial companies to invest in a new technology. They need to form a clear business case by identifying market opportunities and understanding the risks, timescales, skills and investment required. These are all challenging when a new technology's performance is not yet good enough to meet market demand, and its future performance is not readily predicted.

It is essential that industry is engaged from the outset. In the early stages of research the capabilities of the technology will not be fully understood and the markets may not exist. Industry has a vital role to play in identifying not only where quantum technology can apply to existing markets but also the new markets and business opportunities that quantum technology might bring about. To generate new business opportunities we need constant dialogue and close cooperation between those who understand the capabilities of the technology and those who appreciate the dynamics of new products and markets.

To involve companies before the benefits and opportunities of a new technology are known requires intelligent intervention with public financing – one reason the alliance needs its third partner, government.

**GOVERNMENT**

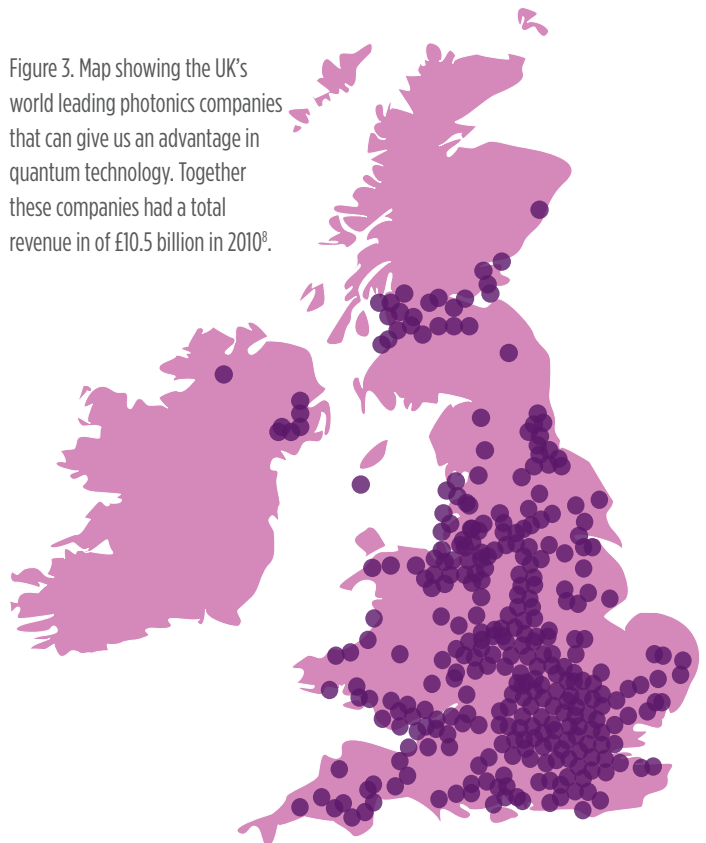
Many of the quantum technologies in this report have existed in the lab for 20 years or more, and research has brought the technology to a point

## In the UK, quantum technologies already have a small but growing following of companies who want to be either first to market or first adopters

where there are now many possible commercial applications. But as these applications are so new, and often disruptive, the route to realising them is still quite uncertain and carries risk. This makes companies cautious about investing.

Market inertia can be overcome by increasing coordination between the academic and industry communities, raising the profile of the sector and by funding demonstrator projects. Government has an important role to play in all of this. For instance, government can act as an early adopter of quantum technologies. Government support, such as through the National Programme and Innovate UK, can reduce the risks for companies developing these technologies, encouraging a longer-term

Figure 3. Map showing the UK's world leading photonics companies that can give us an advantage in quantum technology. Together these companies had a total revenue in of £10.5 billion in 2010<sup>8</sup>.



view even without clear sight of the journey to market (see map opposite).

This support, combined with close co-ordination and focused effort, can also solve an impasse in the supply of components. Many components needed in quantum technology are highly specialised, with no existing manufacturers. Until there is a market for quantum technologies there will be no incentive for companies to make these components – but the lack of components hinders the identification of market opportunities. Companies can be incentivised to develop components before they have full sight of the potential markets, and so complete the supply chain.

## Bringing academia, industry and government support together in one place can enable a free flow of ideas, the pooling of people and access to shared facilities

These interventions are most effective when they have the aim of making the UK an attractive place for new businesses to grow, by attracting inward investment, and ensuring that core research and early commercialisation activities are seen as fertile ground for investment by international companies.

In this way, government support can help to bridge the gap between academia and industry, and create the right environment for their cooperation, accelerating the launch of our quantum technologies industry.

### THE QUANTUM ECOSYSTEM

Quantum technologies can flourish if the emerging industry is supplied with the necessary skills, supported by standards and rooted in clusters.

### CLUSTERS

Bringing academia, industry and government support together in one place can enable a free flow of ideas, the pooling of people and access to shared facilities. This can accelerate the development and adoption of emerging technologies. Clusters make a useful one-stop-shop for potential collaborators, employees and private finance.

In the UK, there are already signs of quantum technology clusters appearing around the quantum hubs led by Birmingham, Glasgow, Oxford and

York, as well as around Southampton, Bristol, Cambridge, Adastral Park and London (UCL and Imperial College). Although they have begun to grow organically, it is essential that these clusters are nurtured. Providing them with the money and skills to develop and grow is a highly efficient use of public funding.

Investment should adapt and evolve with the emergence of surrounding companies. Cluster centres, such as the quantum hubs, must provide a knowledge base for new companies and fuel the interdisciplinary working and knowledge exchange to bring products and services to maturity.

Coordination will become increasingly important as the work evolves, and as areas of overlap appear. In time the hubs will evolve from a mechanism to coordinate research to a means of ensuring coordinated market access. We should be aware of developments happening in clusters overseas, such as those in Waterloo, Ontario and in Silicon Valley, California.

The UK should continue to enable virtual clustering, through the UK special interest group run by the Knowledge Transfer Network, and dedicate resources to providing information and guidance, such as news, patent reports and roadmaps.

### SKILLS

Quantum technologies require a new workforce, with special skills and expertise. This workforce will have to be multi-disciplinary, understanding some of the underlying quantum physics as well as having the right blend of skills in design engineering, manufacturing, business and entrepreneurship.

Existing training centres have a role to play, notably the Centres for Doctoral Training, and the Training and Skills Hubs in Quantum Systems Engineering. However, future schemes should not just involve doctoral training. A rich mix of training initiatives will be required, such as apprenticeships, joint industry-academia projects and secondments. An example of such a training initiative within the UK landscape is the Quantum Technology Enterprise Centre (Bristol, Cranfield), which involves MBA-level education combined with training in systems engineering and design.

### STANDARDS AND ASSURANCE

Standards are essential in complex systems to ensure that equipment and protocols all work together, with each component performing its function. New standards are needed to integrate

quantum communications into networks; while for quantum clocks, sensing and computing, standards will be needed to accelerate the adoption of these technologies in existing IT systems. Verification through testing and evaluation, leading to certification by an independent third party, ensures that a product conforms to an appropriate standard. This assures customers that products and services are fit for purpose.

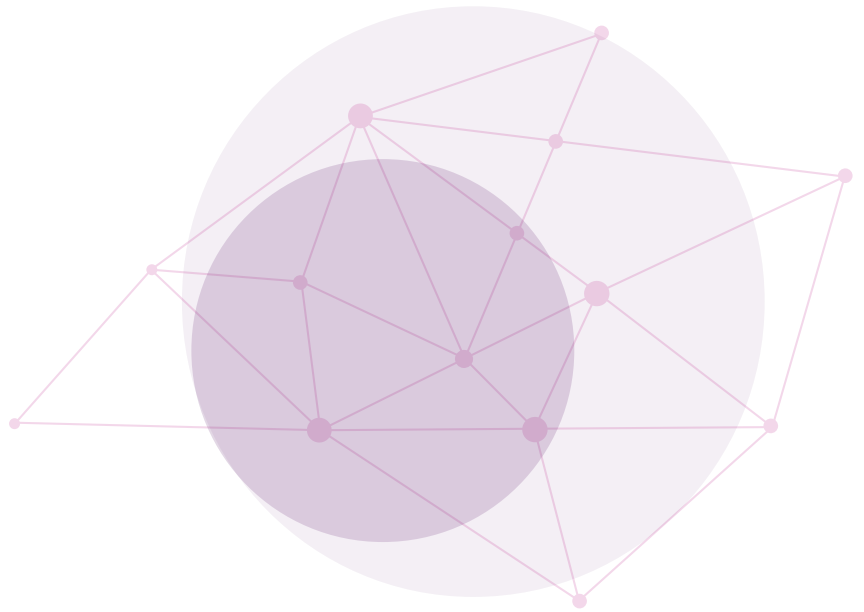
In cryptography, for example, standards will assure users that the technology is secure from cyber-attack. The UK has been leading the development of international standards for quantum key distribution. It is important now to build on this expertise by establishing the infrastructure required to perform conformance tests and issue accreditation certificates.

Standards can also stimulate a supply chain for components, assemblies and applications, through the definition of common interfaces. Again in communications, defining the requirements and performance of the internal components will allow a market for quantum sources and detectors to develop. Similarly, a standard interface for the delivery of quantum crypto keys or time signals will allow third parties to integrate quantum technologies into existing systems or to develop new applications. So appropriate standards can drive innovation in the adoption of quantum technology, and spur growth in the market.

Creating meaningful standards requires a real product or prototype and should therefore be driven by vendors and end users, but government can stimulate this process by commissioning pilot projects to deploy the technology. It can also fund applied research addressing standardisation problems in metrology labs, industry and academia, for example studying integration of quantum communications in data networks or quantum clocks in finance systems. Government should also consider funding participation in standardisation bodies.

### THE WAY FORWARD

The opportunities and risks of the UK vote to leave the European Union should be considered in relation to the National Quantum Technologies Programme. The collaborative nature of research means that it is important for the programme to



remain outward-looking, given the benefits that international engagement brings.

New facilities could be established to evaluate emerging quantum technology products. That would promote skills and expertise, encourage the growth of value-added services, and support essential standards-making. These facilities could give hands-on training to engineers and technicians in the integration of quantum technologies, and be the first point of contact for industrial partners and entrepreneurs seeking new market opportunities.

Finally, the UK quantum technologies programme could benefit from greater coordination at a national level. A team should be established with the sole remit to coordinate activities across the programme. This team could help to prioritise spending and resources; respond to national and international developments; link government horizon-scanning to projects, competitions and demonstrators; and coordinate the purchase of scientific equipment.

### CONCLUSIONS

Together these steps should ensure that the UK develops a strong ecosystem of ideas, people, technologies and facilities to fuel the development and uptake of quantum technologies. We want our quantum technologies industry to be so deep-rooted in the UK that it will flourish here for many decades. The more we invest now, the greater and stronger those roots will become. The investment should be repaid well through the growth of companies supplying or adopting quantum technologies, to secure economic and social benefit for the UK.

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- 6 Publication profiling of UK quantum technologies research; EPSRC and Digital Science; April 2015

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- 7 Emerging Technologies: Quantum; Intellectual Property office; January 2016

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