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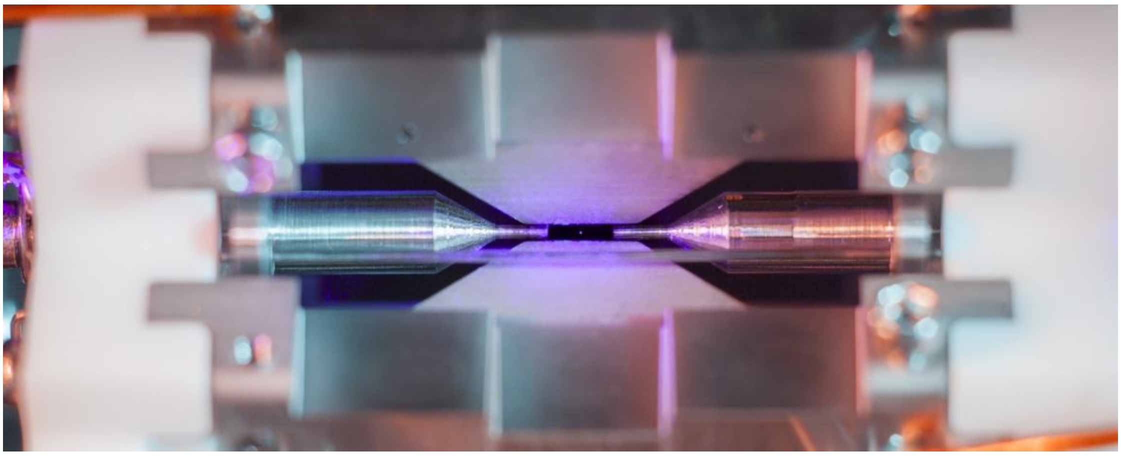
Quantum computing, sensing and communications



Overview

- Recent scientific advances have allowed new ways to control objects at the scale of atoms. At this scale, quantum effects come into play. These developments have profound implications for technologies underpinned by quantum physics.
- Quantum computers may be able to solve problems unfeasible for conventional computers. However, data encryption methods used in applications such as finance may not be secure against quantum computers, perhaps within the next 10 years. The UK National Cyber Security Centre has recommended that organisations start to move to 'post-quantum cryptographic' methods now.
- Quantum technologies could be transformative. In healthcare, quantum technologies could mean ultra-sensitive and earlier diagnoses, and potential treatments for diseases such as cancer and Alzheimer's disease.
- The UK invested over £1 billion into quantum technologies to 2024. Between 2012 and 2022, the UK Government estimated that 12% of global private investment in quantum technologies was directed to the UK. The 2023 UK National Quantum Strategy committed £2.5 billion for the next 10 years.
- Stakeholders say there is a need for interdisciplinary skills, responsible innovation, and adaptable regulation to address potential harmful use of quantum technologies, and to maximise public benefit.

Background

Many everyday items, such as computer processors, LED lights, and accurate timekeeping are underpinned by quantum physics, the rules that describe the behaviour of very small objects (box 1).[1,2]

Scientific advances in the last decade have led to a new generation of technologies, such as more reliable quantum computers, and quantum-enabled brain imaging, that directly use quantum effects.[a] [3,4]

Quantum technologies may, for example, enhance cybersecurity,[5] enable new, less invasive medical technology,[6,7] and solve complex problems in biology, chemistry, physics and finance beyond the capabilities of conventional computers.[8–10]

Box 1: What is quantum physics?

The rules that describe the everyday world are different to those at small scales, such as the size of an atom. The rules that describe larger scales are often called 'classical physics' and those at the small scale 'quantum physics' or 'quantum mechanics'.

Quantum physics was developed in the first 30 years of the 20th century[b] to explain unexpected results from experiments on atoms, molecules and materials that could not be explained with classical physics.[c] [13]

It has been one of the most successful and accurate theories of all time. In some cases predictions agree with experiment to around one part in 1,000,000,000,000.[14]

Objects at quantum scales behave very differently to those in the everyday world, and these effects can be exploited to make products with novel properties. Two examples of effects that can be exploited are 'quantum entanglement', and 'quantum superposition' (see box 3).

Between 2012 and 2022, the UK attracted 12% of global private investment into quantum technologies.[15,16] In 2024, consulting company McKinsey said the global market for these technologies could reach £40 billion to £90 billion by 2035, with quantum computing potentially generating economic benefits between £700 billion to £1,600 billion.[17] In 2024 consulting group BCG estimated economic benefits of £350 billion to £670 billion for quantum computing.[18]

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[a] The UK National Quantum Technologies Programme (box 2) defines quantum technologies as "[…] developments based on controlling nature at the molecular level of atoms, photons, electrons and condensed matter [box 3]. It is the world not explained by Newton's laws of motion, thermodynamics or Maxwell's equations of electromagnetism."

[b] Some important scientists in the development of quantum mechanics were Albert Einstein, Max Plank, Werner Heisenberg and Niels Bohr, among many others. UK pioneers include Paul Dirac, David Deutsch and John Stewart Bell.

[c] For example, radiation from very hot materials, or the emission of light from atoms.[11,12]

In its 2023 Science and Technology Framework, the UK Government identified quantum technologies as one of five critical technologies, alongside artificial intelligence (AI) and engineering biology.[19]

The government has invested £1 billion in research and commercialisation of quantum technologies since 2014 through the National Quantum Technology Programme (NQTP).[20] The NQTP facilitates collaborations between industry, academia and government through quantum technology hubs.

Box 2: The National Quantum Technologies Programme

The National Quantum Technologies Programme (NQTP) supports UK quantum technology research and helps industry identify UK research priorities. It was established in 2014 and operates in five-year phases, with £160 million announced in July 2024 for its third phase.[d] The NQTP now supports five university research hubs to connect research with industry. The hubs specialise in different research areas:

- Quantum Biomedical Sensing Research Hub
- Hub for Quantum Enabled Position, Navigation and Timing
- Hub for Quantum Computing via Integrated and Interconnected Implementations
- Quantum Technology Hub in Sensing, Imaging and Timing
- Integrated Quantum Networks Research Hub

The 2023 National Quantum Strategy committed £2.5 billion in funding for the next 10 years.[15] The strategy was followed later in the year with five 'Quantum Missions' to guide development in areas such as quantum computing and quantum health.[22] In 2023, the UK Government launched the Office for Quantum in the Department for Science, Innovation and Technology (DSIT) to oversee these efforts.[15]

Government-commissioned studies in 2017 and 2024 found that public understanding of quantum technologies was limited, with many participants associating them with science fiction rather than practical applications.[e] [23,24]

[d] The funding includes £106 million from the Engineering and Physical Sciences Research Council (EPSRC), Biotechnology and Biological Sciences Research Council (BBSRC), Medical Research Council (MRC), National Institute for Health and Care Research (NIHR), and £54 million from industry investment.[21]

[e] The 2024 study surveyed 1,013 people online and spoke with 43 participants in workshops. The 2017 study gathered its information from 77 participants attending workshops across the UK.

What are quantum technologies?

Quantum technologies rely on quantum effects to operate (box 1 and box 3). Some established technologies already operate using quantum principles, such as lasers. But these are usually distinguished from the latest generation of devices that sometimes make use of specific quantum effects such as 'quantum entanglement' and 'quantum superposition' (box 3).

Quantum technologies can be split into three categories:

- **Quantum sensing:** concerned with sensing and measuring the environment
- **Quantum computing:** provides novel ways to perform efficient computations
- **Quantum communications:** transmits quantum information

Quantum technologies can enhance existing technologies, such as by sensing weak magnetic fields in brain imaging, or provide novel capability, such as quantum computing.[25,26]

Box 3: Glossary

Quantum technologies include terms from physics, engineering and computer science, among others:

- **Atom**: a single particle of a single chemical element. An atom consists of a nucleus of protons and neutrons, surrounded by a cloud of electrons. These 'subatomic particles' can move between discrete energy levels in 'quantum jumps'. Atoms are typically less than a nanometre[f] in size.
- **Photon**: a particle of light.
- **Entanglement**: a quantum effect whereby two or more quantum objects become interlinked. The properties of one object cannot be described independently of the others, no matter how far apart they are.
- **Superposition**: a property of waves. Two overlapping waves added together are in superposition. A quantum object is wavelike and may be in superposition with other objects, or even with itself.
- **Wave function**: a mathematical description of a quantum object. The wavefunction is related to the probability of finding the object in a particular state, often written in terms of position.
- **Algorithm**: a set of mathematical instructions that can be simple, like adding two numbers, or extremely complex, such as in a machine learning model.
- **Photonics**: analogous to electronics, but for the production, detection, manipulation, and analysis of light instead of electricity.

[f] One billionth of a metre, or 0.000000001 m.

- **Bit**: a bit is a 'binary digit', and can have a value of 0 or 1. Is it the simplest amount of information that can be stored or manipulated in a conventional computer. Eight bits is a 'byte'.
- **Qubit**: a 'quantum bit', analogous to the 'bit' but used in quantum computing. A qubit can be put into superposition and entangled with other qubits.

How do quantum technologies work?

Quantum sensing

Quantum objects are sensitive to their environment. They can be exploited to make devices that can sense, measure or image their surroundings to a standard not otherwise possible with conventional approaches.[27] Quantum sensors include navigation and timing equipment. For example, the National Physical Laboratory (NPL) maintains the UK official time using atomic clocks, machines that precisely measure quantum objects, such as atoms, to count time.[g] [28,29]

Quantum computing

Conventional computers calculate by manipulating 'bits' of information in a step-by-step manner, where each bit can be in one of two states, typically 1 or 0.[h]

Quantum computers represent information using quantum bits, or 'qubits'.[30]

They can have two states like a conventional bit, but qubits can be manipulated to be in a combination of 0 and 1 by exploiting a quantum effect called superposition (box 3). Because each qubit can be in a more complex state than a bit, quantum computers could process considerably more information at one time than conventional computers with an equivalent number of bits.[31]

The complexity of the qubit state increases very quickly with the number of qubits in the system, making certain problems like codebreaking feasible.[i] [32] However, not all

[g] Atomic clocks measure how many times an electron in an atom moves between two energy levels. One second is defined as 9,192,631,770 transitions between two energy levels in a prepared caesium atom. One atomic clock at the NPL is accurate to one second in 158 million years, with one at NIST in the US accurate to one second in over 300 million years as of 2024.[28]

[h] 1s and 0s in a microchip are often represented as high and low voltages. When bits are passed through a complex series of 'logic gates', microscopic constructions in the silicon that manipulate bits in a specific way, the microchip can perform arithmetical operations, such as adding.

[i] Fully describing the superposition state of 300 qubit quantum computer would require more conventional bits than all the atoms in the universe (using the typical precision of common conventional computers). However, measuring each qubit to get a final output would give only a 0 or a 1, meaning all this information cannot be easily accessed.

problems can be improved with quantum computing, such as simple arithmetic.[31] Some commentators say quantum computers will work alongside conventional computers rather than replace them.[33–35]

Due to the sensitivity of quantum systems to their environment, qubits can lose their state due to outside disturbances, or noise.[36] Some researchers have attempted to perform quantum computations despite this noise,[24] but others favour dedicating a fraction of the overall qubits solely for error correction.[j] [38,39]

Some simple quantum computers can currently be accessed over the internet via 'Quantum-as-a-Service' (Qaas) systems.[k]

Some organisations say they have achieved 'quantum supremacy', the moment at which quantum computers can solve problems that would take conventional computers an unfeasibly long time. Google, D-Wave Systems and the University of Science and Technology of China have made this claim since 2019, and in 2023 IBM said they had evidence of 'quantum utility'.[l] [41–44]

However, other experts say that conventional computers are still faster.[45,46] Some researchers say 'universal', programmable quantum computers are up to a decade away, or more.[47,48]

Quantum communications

Quantum communication is the transmission of quantum objects, such as qubits, from A to B.[49] Uses include sending sensitive messages securely across the country, or sending information between quantum computers that could not be sent with conventional computers.[33,49,50]

Research has shown that quantum communication could improve quantum sensors by directing the output into a quantum computer.[51]

Some industry experts say quantum communications research could create a 'quantum internet', which would communicate with quantum objects and serve both civilian and military use.[50,52]

Position, navigation, and timing

Position, navigation and timing (PNT) systems can provide precise data on location and time.[53] They are primarily underpinned by the Global Navigation Satellite System

[j] Some quantum computers use some of their total number of qubits for error correction. Quantum computing power can be difficult to assess when only comparing qubit numbers.

[k] Companies that offer this service include IBM, Microsoft, and Oxford Quantum Circuits in the UK. Full details about how each company's technology operates is not publicly known. QaaS calculations use contributions from classical computers to determine their output.[40]

[l] Quantum supremacy is sometimes known as 'quantum advantage'. IBM refers to 'quantum utility', the moment quantum computers can perform useful, reliable computations at scale.

(GNSS).[m] [54] They are important for financial trading, mobile networks, power grids and transport logistics.[53,55] Research commissioned by the UK Government in 2023 determined that a GNSS outage could cost the UK economy £1.4 billion per day (table 1).[56]

Quantum technology is used in some PNT systems. For example, every GNSS satellite has an atomic clock.[57] As part of the formation of Australia–UK–US partnership (AUKUS) in 2022, the UK Government announced the 'AUKUS Quantum Arrangement' to accelerate quantum research with an initial focus on PNT, and an aim to trial "emerging quantum technologies […] in the next three years".[58]

The 2025 HM Government National Risk Register identified PNT services as critical to UK infrastructure,[59] and a framework for greater PNT resilience has been in place since 2023. In 2025, the UK Government said the framework "remains in place", including commitments to create a National PNT Office and a PNT crisis plan, and to "investigate possible options for a UK sovereign regional satellite system".[60]

PNT for the stock market

High-frequency trading (HFT) in UK financial markets requires timestamps accurate to a 10th of a millisecond of UTC time.[n] [61] This accuracy is maintained through a UK network of atomic clocks that are synchronized using signals in fibre networks.[63]

Table 1

Sector	UK economic loss per day of GNSS outage
Emergency Services	£883.5 million
Road transportation	£333.2 million
Maritime	£95.3 million
Finance	Less than £1 million
Agriculture	Less than £1 million

Source: London Economics, commissioned by InnovateUK with the UK Space Agency and the Royal Institute of Navigation.[56]

What are possible future uses for PNT?

Risks to GNSS access could be natural, such as from solar storms, or deliberate, such as from cyber-attacks.[64,65] Typical GNSS signals cannot penetrate very far underground or underwater, limiting its use.[66,67] By developing sufficiently precise sensors, clocks, and navigation systems, independent PNT systems could provide backup capabilities, and provide new use cases.[54,68]

[m] The Global Positioning System (GPS), owned by the United States Space Force, and the Galileo satellite network, run by the European Union Agency for the Space Programme, are examples of GNSSs.

[n] As specified by Markets in Financial Instruments Directive (MiFID) trading regulations, specifically MiFID II.[61,62]

Aircraft safety

A trial of an optical atomic clock for aircraft using technology designed and built in the UK was reported by the UK Government in May 2024.[69]

Extending submarine dive periods

Submarines cannot contact GNSS systems for extended periods of time. Given an initial dive position, they use various sensors to navigate onwards – known as 'dead-reckoning'.[70] Security experts say precise quantum sensors could extend the time a submarine can remain submerged.[o] In October 2024, the Royal Navy announced a successful sea trial of a UK-built quantum sensor that could allow vessels to operate in "GPS denied or degraded environments".[71]

Track monitoring on the London Underground

Current track monitoring on the London Underground requires specialist vehicles that cannot accurately match the track condition to their location.[72] A UK startup working with Transport for London is incorporating quantum PNT devices for use on passenger trains to monitor the track.[p][74] A stakeholder from Transport for London said this could help to detect faults early, reducing maintenance costs and delays.[72]

Quantum technologies in healthcare

Quantum sensors are now used in medicine and healthcare and are an active area of research.[75] In late July 2024, the Secretary of State for DSIT announced over £100 million in funding for five quantum hubs around the UK (box 2), with the Quantum Biomedical Sensing Research Hub[q] aiming to explore "quantum sensors for ultra-sensitive disease diagnosis […] and biomedical scanners to facilitate earlier diagnosis and treatment of diseases such as cancer and Alzheimer's disease".[76]

One of the UK National Quantum Strategy Missions states: "By 2030, every NHS Trust will benefit from quantum sensing-enabled solutions, helping those with chronic illness live healthier, longer lives through early diagnosis and treatment."[22] Other examples are:

Wearable quantum sensors for brain imaging

Magnetoencephalography (MEG) is a non-invasive brain scanning technique.[77] MEG measures the magnetic field of nerve impulses, but requires expensive cryogenic cooling and large scanners. UK researchers have developed wearable brain scanners using quantum technology that operate at room temperature and allow the patient to move.[25]

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[o] Inertial navigation is the process of computing a final position by measuring the orientation and acceleration of the submarine. This is supplemented with environmental information to help calibrate map position.

[p] This technology has been tested on the Circle line.[73]

[q] Based in University College London and the University of Cambridge.

The technology has been used to study brain development in children.[r] [78] A UK university spinout company is pursuing medical certification for clinical use.[s]

Breast cancer screening

UK researchers are developing more affordable breast cancer screening methods by exploiting quantum effects to image breast tumours with entangled photons (see box 1).[79] With this method, one photon interacts with an object to be imaged, such as the tumour, and the other will be detected by a camera.

As the detected photon shares properties with the photon that interacts with the tumour, it is possible to determine the properties of the tumour from its entangled partner.[80] The entangled photons can also be produced at different energies, with one produced at an energy most suitable for detecting breast cancer, and the other can be at an energy detected by standard commercial cameras.[81]

Quantum technologies and machine learning

Machine learning (ML) models, a type of artificial intelligence, are computer programmes that find patterns in large sets of data (POSTbrief 57). They are now being used in applications such as powering chatbots, solving protein folding problems, and creating scientific models.[82,83] The rapid progress of ML has prompted researchers to ask whether quantum technologies and ML could benefit each other.[84,85]

Can machine learning improve quantum computers?

Machine learning (ML) is being used to overcome challenges in developing quantum technologies.[86] UK researchers have used ML to characterize quantum devices by detecting material imperfections.[87] This information can guide adjustments to improve device performance. ML algorithms can also help optimise the operation of quantum computers.[88,89]

[r] MEG scanners are typically unsuitable for children as they require patients to be still. MEG imaging for children had previously been found to be impractical.

[s] A university spinout company is formed when university research is used as the basis for a new company. It often employs university staff and can involve the transfer of intellectual property from the university to the company. In this case, the company is Cerca Magnetics in Nottingham.

Can machine learning improve the use of quantum sensors?

ML methods can be used to optimise sensor performance and process their outputs.[90] For example, UK researchers are developing quantum magnetometers[t] to detect pipe defects by measuring changes in the magnetic response caused by cracks.[91] They reduced survey times by using ML to guide the search patterns.[92] This application could help improve water infrastructure.[u] [93]

Can quantum computers complement machine learning?

Quantum computers could enhance the training or operation of conventional ML in two ways:[33]

- Data generation for training ML models: quantum computers could be used in some instances to create synthetic (simulated) training data that would be impractical to generate using conventional computers.
- Hybrid processing: quantum computers could handle intensive tasks that feed into larger conventional ML systems.

How can quantum technologies be used in products?

The National Quantum Technologies Programme (NQTP, box 2) supports fundamental research and commercial development of quantum technologies.[97] Some technologies may also be 'dual-use' (box 4).

Box 4: What are dual-use technologies?

Civilian technologies that can be used for military purposes are 'dual-use' technologies. For example, night-vision equipment, or rocket engines. They may be physical goods or software, and export from the UK is often controlled.[94–96]

Quantum sensing

Some industry experts said quantum sensing is the most widely commercialised quantum technology (table 2).[98–100] There are now several commercially available sensing devices, as well as live demonstrations and prototypes. Depending on the

[t] Sensors that detect magnetic fields.

[u] The water regulator Ofwat reported that around 20% of treated water was lost to leaks in 2022.[93]

application, quantum sensors may either improve conventional sensors through 'sensor fusion',[v] or operate independently.[101]

Table 2: Sensors

Type	Example: civilian use	Example: defence and security applications
Lidar with single photon detection: Lidar systems produce light pulses to map surroundings, analogous to how bats can 'see' using sound echolocation.[102] By being able to detect a single photon, they are many times more sensitive than typical light detectors.	**Detecting methane leaks**: methane, per tonne, is more potent as a greenhouse gas than CO_2.[103] A UK startup has developed a camera that detects methane in real-time.[104] Initially tested at oil facilities, the technology might also help monitor methane leaks across landfills and wastewater sites.[105]	**Seeing around corners**: UK prototypes have demonstrated the ability to image objects behind corners.[106,107] This technology could be used in combat scenarios. **Seeing through visual barriers**: UK researchers have developed Lidar methods to map out environments obscured by smoke or camouflage.[108]
Detection of radiowaves: radiowaves and microwaves are examples of electromagnetic radiation,[109] to which highly excited atoms, called 'Rydberg atoms', are very sensitive. Sensors equipped with Rydberg atoms can be used to detect very weak radiowaves or microwaves, for example.[110]	**Enhanced telecommunications antennae**: UK researchers have begun testing new receivers that can pick up weaker signals, or operate across more frequencies.[111,112] Though at an early stage, BT hopes to achieve 100 times more sensitivity than traditional receivers, which would help increase coverage and reduce power consumption.	**Receiver frequency adaptivity**: Security experts say military environments now involve more complex electromagnetic signals.[113] Having a receiver that can rapidly switch frequencies over a wide possible range can offer an advantage.[114] This potential has led to development funding from some US defence research agencies.[115]
Gravity sensing: some quantum sensors are sensitive to acceleration and can detect changes in gravity.	**Active infrastructure surveys**: by looking for drops in the gravity, it may be possible to detect tunnels.[116] **Passive infrastructure surveys**: areas more at risk of sinkholes can be passively monitored.	**Subterranean battlefield sensing**: it may be possible to detect underground tunnels or large hidden underground facilities.[117,118]

[v] For instance, one company within the UK is designing a PNT device with 'sensor-fusion'. Their quantum sensors are highly accurate but take measurements less frequently than conventional sensors. By combining the sensors, the quantum sensor helps to correct navigation errors from the conventional methods.[101]

Quantum computing

While quantum computing hardware remains in its prototype stage, some companies are exploring early commercial applications (table 3).[w]

The Ministry of Defence (MOD) is investigating new data processing capabilities and ordered a quantum computer from a UK firm in 2022.[120,121]

Table 3: Computing Type	Potential civilian use	Potential defence and security use
Quantum (bio-)chemistry and materials calculations: atoms combine with one another to form molecules. Molecules are the building blocks of biology and chemistry. The way atoms and molecules interact is described by quantum physics. They could be simulated by a quantum computer much faster than a conventional computer.[122,123] Also, material properties described by quantum physics may be simulated by a quantum computer.	**Drug discovery**: the way medicine molecules interact with cells, pathogens, or cancers, could be modelled with higher fidelity, and shorter development times.[124,125] **Advanced materials**: Quantum computers could be used for designing photovoltaic cells for use in solar panels.[125]	**Chemical and biochemical weapons**: bad actors could use quantum computers to develop molecules, or pathogens, that are harmful to humans.[126] **Advanced materials**: quantum computers could be used to design lighter or stronger materials for use in aircraft.[127]
Optimisation problems: deciding how best to allocate resources is an example of an optimisation problem. Some of these problems can written using quantum physics equations, which can then be run in a quantum computer.[128]	**Portfolio optimisation**: could be used by financial institutions to compute pricing and composition of their holdings more quickly.[129]	**Logistics optimisation**: could be used by the military to better position their strategic assets.[130]

Quantum technologies for conventional computing and data science

Some UK companies offer devices that measure quantum systems, which are truly random, to generate random numbers. Random numbers are needed in applications like encryption or scientific calculations.[100,131] If the numbers are not fully random and

[w] For example, a UK startup uses existing quantum computers to support real-time music generation.[119]

can be predicted, encryption may not be fully secure, for example.[132] Conventional computers cannot produce true random numbers.[133]

Some commentators think the value of quantum technologies is in the high-quality data it can produce, for instance from monitoring buildings. They say it could also improve the training of machine learning systems.[134,135]

Quantum communications

BT and Toshiba have constructed a commercial communications network for quantum key distribution (QKD) in London (see QKD section).[x] [136] However, some researchers say a general quantum network is a long-term research ambition.[50,137]

In 2016, China was the first country to launch a satellite to test quantum communications in space.[138] This extended their existing fibre-based quantum communications infrastructure from 2000 km to 4600 km.[139] The UK currently aims to launch two satellites in 2025 to perform its own testing.[50,140,141]

Software opportunities for quantum computing

Experts say quantum computers require efficient software, such as algorithms, as well as hardware to make them useful.[33,99,142–145] The number of software programmes is limited.[146]

Why is developing software for quantum computers commercially important?

Manufacturers of quantum computing hardware, such as IBM, believe there is a "gap in the market" for quantum software development.[33] However, developing software without mature, reliable quantum computers can be challenging.[147]

Some industry experts have said quantum computing needs to demonstrate clear advantages over conventional computers within the typical hardware development timelines of around five years before they provide further investment.[33,137,148]

Quantum algorithms

Current quantum software research typically investigates algorithms.[149] However, some practical advances in software are emerging. For example, a UK university spinout has developed methods that could enhance existing chemistry simulations.[150]

Within the last decade, advances in the mathematics of quantum algorithms have allowed researchers to estimate the resources required for computation.[151,152] These

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[x] If the key that is used to decrypt information is shared using quantum objects, the process is called quantum key distribution (QKD).

estimates help guide quantum software design, set realistic expectations, and verify the feasibility of proposed computations.[y] [153]

As developing quantum software is cheaper than hardware,[99,100,144] some commentators believe the UK should develop a research strategy for software efforts.[137,149,151] Others point out that some countries, including several without a history of quantum research, have recently begun hardware research programmes despite the known costs.[99,145,154]

Error correction for quantum computing

Algorithm development also benefits from electronics expertise. To ensure useful quantum computations, qubit noise must be reduced.[155] A UK university spinout has designed specialist electronic chips for quantum error-correction that can be installed within various quantum computers.[156]

What are the security concerns for quantum computing?

Sensitive digital information, such as banking details and passwords, are protected by encryption, a process that scrambles data. A key is required to unlock it meaningfully.[157,158] While current encryption methods[z] are considered secure against current and future conventional computers, the UK's National Cyber Security Centre (NCSC) says this data will be vulnerable to a sufficiently powerful quantum computer when available.[aa] [161]

Some experts refer to 'Y2Q', or the 'years to quantum', the date at which a quantum computer can efficiently break conventional encryption. The date is contested, with some expecting Y2Q by 2030, but with many others expecting the date by 2035.[47,48]

In 2024, the NCSC said "for organisations that need to provide long-term cryptographic protection of very high-value data, the possibility of a [powerful quantum computer] in the future is a relevant threat now".[161]

[y] A UK startup recently showed that the resources required for a simulation of advanced materials was a factor of 1 million times smaller than previously thought.[143]

[z] The most common protocol is called "RSA", which works by multiplying two large prime numbers together to make a yet larger number. However, it is very intensive for a conventional computer to reverse the process to find which prime-numbers were used to begin with. It would take a current conventional computer 300 trillion years to break existing RSA encryption.[159]

[aa] Shor's algorithm, an algorithm exclusive to quantum computing, can bypass the conventional encryption. This is beyond the means of quantum computers in at least the medium term.[160]

What can be done?

Post-quantum cryptographic (PQC) methods

The US National Institute of Standards and Technology (NIST) has proposed new cryptographic[bb] standards that are resistant to quantum computers called post-quantum cryptography (PQC) standards.[cc] [163] These standards are endorsed by the NCSC.[164]

Many technology companies, including Apple and Google, have introduced PQC in their software.[165,166] However, PQC requires more costly calculations, which may make older, or low-power, devices incompatible.[162]

Industry commentators say upgrading systems to PQC standards will be complex for organisations, requiring inventory checks and investment.[167] In 2024, the NCSC said the total cost of migration to PQC methods could be "significant". They expect organisations to take two to three years to carry out early migration activities, and recommend complete migration by 2035.

Quantum key distribution (QKD)

Quantum key distribution (QKD) is when an encryption key is sent using quantum objects, such as photons. QKD is meant to complement, rather than replace, PQC.[5,50] As QKD requires a dedicated network[dd] to carry the quantum object, there are additional costs to deployment.[169]

Due to the laws of quantum physics (box 1), any eavesdropper to a QKD message would irreversibly change the system, thereby alerting the user.[169] This security offers a safeguard against future technological advances.

Security asymmetries

One researcher from the think tank RAND said that the first country to develop quantum computing may gain an intelligence advantage, but it is unlikely to be decisive.[170] They said developments in PQC can happen independently to advances in quantum computing.

[bb] Cryptography studies combinations of mathematical operations that are easy to verify but difficult to guess.[162] Cryptographic methods underpin vital technologies such as encryption.

[cc] Some experts raise concerns that, given the early stage of quantum cryptography, a future sudden breakthrough could render any given cryptographic standard ineffective.[50] However, the same experts also confirm that there are no formal proofs for the general safety of RSA encryption under conventional computing, which has successfully secured our data against conventional computers since 1982.[125,162]

[dd] This will likely be in the form of specialised fibre cables; however, there is active work to send the signals through air or space.[168]

The National Quantum Computing Centre

The government opened the National Quantum Computing Centre (NQCC) in October 2024, providing £143 million of initial funding.[171] The NQCC's remit is to:[172]

- procure quantum computing systems, which helps to provide an initial market for the technology
- provide researchers access to prototype quantum computing devices to perform tests and research
- horizon scan to determine which quantum computing methods are most likely to be successful, and to then direct funding accordingly

The NQCC also validates quantum computing systems and programmes.[ee] [173] It runs the 'sparQ' user engagement programme to gather feedback, find quantum solutions (such as optimising the allocation of NHS beds), and build quantum computing community networks.[173,174]

The primary focus of the NQCC is on quantum computing hardware, but the centre sometimes collaborates with software research groups, such as Edinburgh University's Quantum Software Lab.[145]

Skills for quantum technologies

Quantum technology development requires diverse technical expertise in, for example, physics and engineering.[175] Industry commentators say some jobs within the quantum technology sector, such as technicians, are not limited to university graduates.[175,176]

For quantum computing, some experts say theoretical research continues to be an important part of its development.[149,151,177–179] In particular, they say quantum algorithm development requires strong interdisciplinary theoretical knowledge in physics and mathematics.[ff] Others say the UK's reputation in mathematical sciences continues to attract researchers to these fields.[170,180,181]

A 2022 EY survey of businesses adopting quantum technologies identified accessing talent as their most significant concern.[182] In 2024, a review by the Royal Academy of Engineering highlighted concerns from industry about a shortage of quantum-relevant skills.[183]

The NQTP (box 2) has supported over 570 PhD studentships, including over 60 MOD projects.[184] Additionally, a DSIT quantum apprenticeship programme is to start in

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[ee] This is currently done by comparing the results with a conventional computer. However, as one day quantum computers will run some problems much faster, the NQCC is researching ways to perform this validation without the need to run conventional computers.[173]

[ff] Similarly, the UK bank Standard Charter have not always been able to fill research vacancies for quantum computing applications due to the small number of qualified people.[129]

2025 to complement existing National Physical Laboratory apprenticeship schemes that include technical training in quantum technology.[16,185,186]

In 2023, the Commons Science, Innovation and Technology Committee inquiry into commercialising quantum technologies heard the value of researchers gaining commercial training through the University of Bristol Quantum Technology Enterprise Centre (QTEC), funded by the NQTP.[187] QTEC said they helped create a third of UK quantum startups until operation ended in 2022.[gg] [188]

UK coordination of quantum technologies

The UK was the first nation to have a NQTP (box 2). Other nations have since adopted similar schemes.[185,189] Some researchers have stated there is a lack of similar coordination in research for the materials used for quantum technologies, or for quantum algorithms and theory.[125,149] For instance, software for quantum computing, which includes algorithms, is no longer included within the current hubs.[99,190]

However, some university researchers outside the hub have said that they are not greatly affected and can still engage with the NQTP.[191] For instance, the EPSRC-funded 'Materials for Quantum Technologies' network was set up to connect university researchers from materials science and quantum technologies.[125,192]

Public perspectives on quantum technologies

The UK Government conducted its first public dialogue on quantum technologies in 2017, with a follow-up study focusing on quantum computing in 2024.[23,24] The 2024 study found increased public recognition of the term "quantum computer", but understanding of its functionality remained low.

Researchers attempting to form spinouts have shared difficulties in finding business support, such as financing, due to the confusion that 'quantum' brings.[193] The different areas of quantum technologies have unique challenges,[hh] and like other advanced technology areas like AI, quantum technologies require specialist knowledge from investors.[100,193,194] Some industry experts have advocated for integrating quantum technologies into business courses, such as MBAs, to help ease cooperation.[193,195]

[gg] Since its closure, some of the training from QTEC has been incorporated into the business incubation network, SETsquared Bristol, run by five universities in south England.

[hh] Some stakeholders shared that some venture capital investors had assumed that the same requirements for quantum sensing would be the same as quantum computing, despite being distinct technology.

UK manufacturing

A 2023 report by UK Photonics stated that the UK photonics sector is worth £15 billion.[196] Much of this manufacturing is based in Scotland. Wales also hosts specialist manufacturing capabilities for advanced materials within quantum technologies, particularly in industrial diamond and semiconductors.[183]

Quantum manufacturing relies heavily on global supply chains and is vulnerable to disruption (POSTnote 721).[197]

Materials science

Materials science is an interdisciplinary research area that aims to understand and exploit material properties using chemistry, engineering, and physics, and is important to some quantum technologies.[198]

The growing commercial need to effectively package quantum technologies, often by shrinking, is a problem that some commentators say materials science can help with.[125,183]

Businesses and universities have access to specialised equipment and technical expertise to support the development and measurement of advanced materials through UK facilities such as the Henry Royce Institute, or NPL.[199,200]

Current policy and legislation

In response to recommendations from the Regulatory Horizons Council, the government said in October 2024 that future regulations "should focus [on] developing application-specific regulatory frameworks that are adaptable and proportionate to the properties of individual innovations and their stage of development", similar to its approach to regulating artificial intelligence.[201]

Existing legislation to prevent misuse, such as the Computer Misuse Act 1990, Data Protection Act 2018 and Investigatory Powers Act 2016 are technology-neutral and will continue to apply.[202–206] However, some researchers maintain the need to 'horizon scan' as the technology develops.[207]

Policy considerations around dual-use

Dual-use technology (box 4), including quantum technology, can be subject to export restrictions under the Wassenaar Arrangement.[ii] [208] Export of quantum computers was further restricted over national security considerations within the Export Control (Amendment) Regulations 2024.[209] Also, the exports and foreign investment of UK quantum businesses are subject to additional oversight with the National Security and Investment Act 2021.[210] However, some commentators warn that excessive restrictions could limit innovation.[149,211]

[ii] The Wassenaar Arrangement is a voluntary international agreement between 42 countries that aims to control exports of conventional weapons and dual-use technologies.

In 2023, the UK Government announced a US–UK economic partnership called the Atlantic Declaration that stated the UK's aim to "explore joint efforts and collaborative R&D in a range of critical and emerging technologies", including quantum technology.[212] An action plan was published in May 2024.[213]

Some foreign researchers and research students must obtain specific clearances as part of their visa, such as the Academic Technology Approval Scheme.[214] This measure is designed to protect sensitive research. However, theoretical quantum research such as quantum algorithms, and experimental results, are published in publicly available journals. One stakeholder argued that current security restrictions on hiring foreign nationals for theoretical research may be disproportionate given its public nature.[180]

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