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Quantum technologies

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Science and Technology Committee

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Quantum technologies are a group of technologies that make use of the sometimes counter-intuitive behaviour governed by quantum physics, which usually becomes most apparent at very small length-scales. Examples include world-changing technologies such as lasers and computers. Intensive research over the past few decades has improved the extent to which quantum behaviour can be reliably controlled and put to use, enabling the development of a new generation of quantum technologies with superior or sometimes revolutionary capabilities compared to conventional alternatives. This new generation encompasses a variety of technologies, such as quantum clocks, sensors, cameras, computers and communications systems, the first of which are being commercialised now.

Quantum technologies offer the potential for significant economic growth and improved capabilities across multiple industry sectors. The first phase of the National Quantum Technologies Programme has placed the UK in a world-leading position. The Government announced £235m funding for quantum technologies in the 2018 Budget, taking total funding for the next phase of the National Quantum Technologies Programme to £315m. We welcome the Government's decision to support a second phase of the National Quantum Technologies Programme with this funding, which is broadly commensurate with the Strategic Advisory Board's estimated requirements.

Although the first phase of the National Quantum Technologies Programme is widely seen to have been successful, we believe that there is room for improvement in the co-ordination across the Programme. The Government should establish a new Executive Board to oversee the second phase of the National Quantum Technologies Programme. The new Board should have a clearly defined mission statement and be held accountable for delivering on it. The mission statement should include an overall aim to support the development of a UK quantum technologies industry that delivers the maximum economic, national security and societal benefit for the UK public as a whole. The new Board should comprise representatives from academia, small and medium-sized enterprises, large companies, standards bodies, regulators and the Government, including from national security and defence organisations.

The Executive Board should produce a detailed roadmap, or series of roadmaps, for the future potential markets for quantum technologies in the UK, in consultation with appropriate experts from the market sectors identified. The roadmap should assess the likely size and timeframe of each potential market, as well as the technological developments, infrastructure, workforce, supply chains and regulatory measures that are expected to be required to harness each market opportunity. The Executive Board should use the roadmap of future quantum technology markets to identify potential obstacles to the development and commercialisation of quantum technologies in the UK and to define a strategy to overcome these. The strategy should be published and updated alongside the roadmap and include clear, measurable milestones, to be reviewed annually.

We heard wide support for the establishment of Innovation Centres, first proposed by the Government Office for Science, in the second phase of the National Quantum Technologies Programme. The announcements made confirming the extension of

the National Programme into a second phase did not, however, reference Innovation Centres. In its response to this Report, the Government should confirm its intention to set up Innovation Centres and outline how many it intends to establish, which sectors they will cover and what the timeline is for their establishment. While we support the use of suitable existing infrastructure to house Innovation Centres where it can deliver what is required more quickly and at a reduced cost, this should not dilute the concept of Innovation Centres or weaken the drive to establish them as soon as possible.

Innovation Centres should provide access to facilities for developing, manufacturing, testing and validating quantum technologies, as well as act as focal points around which collaboration and supply chains can consolidate. This will require Innovation Centres to exist, at least in part, as physical centres rather than as 'virtual networks'. The Executive Board must additionally ensure that there is good co-ordination between the new Innovation Centres and the Hubs and ensure that technologies are supported through research, development and commercialisation and to provide strategic oversight so that activities in Innovation Centres and Hubs complement each other.

Awareness across industry of the potential for quantum technologies, in particular in the short-term, needs to be improved. The new Executive Board should engage with businesses and industry bodies that are not yet actively pursuing opportunities presented by quantum technologies, articulating the near-term capabilities expected of such technologies and investigating what specific product requirements and technology demonstrations are needed to drive uptake in different sectors. We commend the Ministry of Defence for its support for quantum technology demonstrator projects. Similar opportunities exist for other Government departments. In collaboration with the Chief Scientific Adviser network, the new Executive Board should identify opportunities for Government Departments to support quantum technology demonstrator projects and encourage their uptake by assessing the positive impacts that such projects could achieve for the department and for the UK quantum technologies industry, if successful. We also recommend that the Government fully adopts the recommendations of the Connell Review. The Government should additionally establish a QuantumTech Catalyst to drive public sector organisations' use of the Small Business Research Initiative for quantum technologies, in the same way that the GovTech Catalyst has for digital technologies.

There is significant concern in the quantum technology community that the future development of quantum technologies in the UK could be constrained by the lack of a suitably skilled workforce. This skills shortage is not unique to the UK, and the existing training programmes provided under the National Quantum Technologies Programme are well-regarded, but increasing and improving the training offered must be a priority for the second phase of the National Programme. The second phase of the National Programme must ensure that appropriate training is available at undergraduate, technician and apprenticeship level, alongside continued provision at PhD level. It should provide training opportunities for established workers as well as for those entering the workforce.

The new Executive Board, in co-operation with UKRI, should engage with companies working on quantum technologies or closely related fields to help tailor the content of doctoral training programmes to ensure that they provide the balance of skills needed by industry. UKRI should find ways to make the terms on which industry can input into training programmes more flexible, to facilitate increased engagement. In exchange, UKRI should seek contributions from industry to fund additional studentships.

As with most new technologies, quantum technologies present a variety of potential benefits and risks to society. The National Quantum Technologies Programme's Responsible Research and Innovation (RRI) work should continue into its second phase. All of the National Quantum Technologies Hubs and Innovation Centres should identify an RRI lead responsible for co-ordinating RRI work across the Hub and to act as the primary point of contact for internal and external stakeholders on RRI matters within six months of this Report being published. Each Hub should publish a review of the potential societal impacts of quantum technologies in their sector within a year of this Report being published, to be updated annually.

Quantum technologies have important implications for national security as well as for economic prosperity. The Government must ensure that the second phase of the National Quantum Technologies Programme gives equal priority to benefitting the UK's national security and its prosperity. There should be good co-ordination between military and civil aspects of future quantum technologies in all components of the second phase of the National Programme. Although foreign investment in the UK is almost always benign and welcome, there is the potential for certain transactions that increase foreign influence over British entities to pose significant threats to national security. In addition to the voluntary regime for national security and investment recently proposed by the Government, we recommend that the Government establishes a mandatory notification regime for enterprises researching, developing, producing or supplying services involving quantum technologies, when they are first approached by foreign entities with offers of investment.

1 Introduction

Background

1. Quantum technologies are a group of technologies that make use of the sometimes counter-intuitive behaviour governed by quantum physics,[1] and already include world-changing technologies such as lasers and computers. Intensive research over the past few decades has improved the extent to which quantum behaviour can be reliably controlled and put to use, enabling the development of a new generation of quantum technologies with superior or sometimes revolutionary capabilities compared to conventional alternatives. This new generation encompasses a variety of technologies, such as quantum clocks, sensors, cameras and communications systems, the first of which are nearing commercialisation now.

2. In the 2013 Autumn Statement, the UK government announced an investment of £270m over five years into a National Quantum Technologies Programme "to support translation of the UK's world leading quantum research into application and new industries".[2] The National Programme comprised four National Hubs, spread across multiple networks of universities, as well as Centres for Doctoral Training, funding for innovation and demonstrator projects, and the establishment of a Quantum Metrology Institute at the National Physical Laboratory. The initial funding allocated to the National Programme was due to come to an end in 2019.[3]

3. The Government Office for Science published a review of quantum technologies in 2016, at the mid-point of the initial funding schedule for the National Programme.[4] The report made eleven recommendations, including a conclusion that "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".[5] With the 2019 end-date for the funding of the first phase of the National Programme approaching, we decided to launch an inquiry to assess the opportunity of quantum technologies, the progress of the National Quantum Technologies Programme to date, the case for continuing the Programme into a second phase and, if appropriate, to explore what a second phase of the National Programme should entail.

Our inquiry

4. We received over 30 pieces of written evidence and took oral evidence from 26 witnesses, including academics, research and technology organisations, learned societies, small and medium-sized enterprises, large corporations, representatives from the National Quantum Technologies Programme and the Minister of State for Universities, Science, Research and Innovation. We also visited the University of Strathclyde and the University

1 Behaviour allowed by quantum mechanics includes objects behaving both as particles and waves, existing in a combination of states simultaneously (for example, simultaneously spinning clockwise and anticlockwise), and apparently interacting with distant objects instantaneously.
2 HM Treasury, 'Autumn Statement 2013' (2013), para 1.210
3 UK Research and Innovation (QUT0023), para 2
4 Government Office for Science, 'The Quantum Age: technological opportunities' (2016); The Government Office for Sciencea dvises the Prime Minister and members of the Cabinet "to ensure that government policies and decisions are informed by the best scientific evidence and strategic long-term thinking"—'About us', Government Office for Science, accessed 15 November 2018
5 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p10

of Glasgow to learn more about work being undertaken as part of the National Quantum Technologies Programme. To assist us in our work, we appointed Professor Peter Dobson, Visiting Professor at University College London and King's College London, to act as our Specialist Advisor for this inquiry.[6] We are grateful to everyone who contributed to our inquiry.

5. In this Report, we consider the opportunities for economic growth and societal benefit presented by quantum technologies, as well as the potential risks that must be managed, and make recommendations to the Government regarding the future of the National Quantum Technologies Programme. Specifically:

- Chapter 2 examines quantum technologies and their likely applications, and reviews the progress of the National Quantum Technologies Programme so far and the case for continuing the Programme into a second phase;
- Chapters 3, 4, 5 and 6 set out what the second phase of the National Quantum Technologies Programme should encompass, focusing on governance, Innovation Centres, funding and skills respectively; and
- Chapter 7 discusses the potential benefits and risks to society posed by quantum technologies, and how these can best be managed.

6 Professor Dobson declared his interests on 5 September 2018: Advisor to Bikanta

2 Quantum Technologies and their Applications

6. This Chapter outlines what quantum technologies are and summarises their potential applications, their level of development and what consideration is being given to the wider impact they may have on society.

Quantum technologies

7. Under certain conditions, typically found at very small length-scales,[7] the classical laws of physics that govern everyday behaviour are observed to break down, and the less intuitive rules of quantum physics must be used to predict behaviour instead. This behaviour can be very different from that observed in everyday life, with objects behaving both as particles and waves, existing in a combination of states simultaneously (for example, simultaneously spinning clockwise and anticlockwise), and apparently interacting with distant objects instantaneously.[8] Professor David Delpy, Chair of the National Quantum Technologies Programme's Strategic Advisory Board, told us that to some extent every technology is a quantum technology, "since everything is made up of atoms, which, of course, obey quantum laws".[9] Quantum technologies are generally considered, however, to be those that "harness quantum physics to gain a functionality or performance which […] cannot be explained by classical physics".[10]

8. Quantum physics started to be understood at the beginning of the 20th Century, and it already underpins important technologies such as most electronic devices, lasers, global positioning satellite systems and computers. Despite the significant impact of these existing technologies, the National Quantum Technologies Programme has said that "over the past hundred years we have barely scratched the surface of what quantum technologies can achieve".[11] Research into quantum physics has steadily improved the extent to which the subtler aspects of quantum behaviour can be reliably controlled and put to use, leading to the emergence of a new generation of technologies currently under development. Professor Sir Peter Knight, Emeritus Professor at Imperial College London, explained further:

> We have been using quantum [effects] in lasers, semiconductors and so on for many years. They are quantum enabled, but they do not necessarily exploit what is called quantum coherence. Quantum coherence is the weird ability to put things into superpositions of both here and there […] We are working out ways in which we can get a technological application of the oddities of superpositions, entanglement and so on. That is why sometimes it is called 'quantum 2.0'. It is the next stage [for quantum technologies].[12]

7 The rules of quantum physics must be applied most commonly to predict behaviour that occurs on the scale of individual atoms, although quantum behaviour can be observed at everyday length-scales under other conditions, for example at extremely low temperatures—Richard Feynman, Robert Leighton and Matthew Sands, 'The Feynman Lectures on Physics' (1963), sections I-2–3 and III-4–6
8 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p17
9 Q2
10 Engineering and Physical Sciences Research Council, 'Quantum technologies', accessed 11 July 2018
11 UK National Quantum Technologies Programme, 'Quantum technologies', accessed 13 July 2018
12 Q2

This second generation of quantum technologies comprises different technologies with a variety of applications. The National Quantum Technologies Programme has organised these into four overall fields:

- quantum sensing and metrology;
- quantum-enhanced imaging;
- quantum communications; and
- quantum computing.[13]

Uses in each of these fields are outlined below.

Quantum sensors and metrology

9. Professor Knight explained that achieving the "quantum coherence" needed for the next generation of quantum technologies was "really hard", because the more components a quantum system contains, the more effectively it "talks" to its surrounding environment—and this interaction with the outside environment must be carefully controlled to preserve the coherence.[14] However, he noted that "defects in one place [can] become advantages in others", explaining that this extreme sensitivity to the external environment is a quality that "makes a really great sensor".[15] Hence one initial use for quantum technologies is for sensing and measuring things such as electric, magnetic and gravitational fields, air pressure or the presence of specific chemicals, with extreme accuracy.[16] Indeed, Professor Delpy specified that quantum sensors offer "a way of approaching the real, fundamental limits of measurement and sensing".[17]

10. The range of quantities that can be measured offers a diversity of potential applications for quantum sensors. Professor Kai Bongs, Director of the Quantum Technology Hub for Sensors and Metrology, gave examples of applications in the construction and healthcare sectors to illustrate the potential uses for quantum sensors:

> On infrastructure productivity, we see large potential in removing uncertainty about underground conditions as a major risk in infrastructure projects, and in helping rail projects such as HS2 or the development of houses on brownfield sites to go quicker. In the healthcare domain, magnetic sensors allow you to look into the brain and learn about brain functionality, and open up pathways for new diagnostics that range from concentration deficits in children to dementia in the ageing society.[18]

The National Quantum Technologies Programme has additionally highlighted opportunities for quantum sensors in natural resources discovery, environmental monitoring and earthquake prediction, navigation and defence.[19]

13 UK National Quantum Technologies Programme, 'UKNQT Hubs', accessed 13 July 2018
14 Q2; the surrounding environment encompasses anything that could disturb the quantum system in question, such as neighbouring atoms or electric or magnetic fields
15 Q2
16 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p38
17 Q2
18 Q223
19 UK National Quantum Technologies Programme, 'A roadmap for quantum technologies in the UK' (2015), pp13–14

Quantum-enhanced imaging

11. Increased control of quantum effects also offers opportunities to improve upon the capabilities and resolution of conventional imaging systems. In its 2016 report on quantum technologies, the Government Office for Science highlighted several examples of potential quantum-enhanced imaging systems and their possible applications, including:

- cameras capable of imaging through obscuring material such as dirty water or fog, one use of which may be to help guide autonomous vehicles;
- cameras that can see around corners, with military and civilian uses;
- cameras that can take 3D images, with applications including prototype development in manufacturing and improved robot capability;
- cheap, portable sensors for imaging invisible gases, which could be used to detect leaks; and
- medical imaging systems that avoid the need for harmful radiation.[20]

Quantum communications

12. Professor Tim Spiller, Director of the Quantum Communications Hub, told us that the motivation behind quantum communications technologies is "all about [providing] secure communications".[21] The technologies being developed for communication seek to make use of the fact that the quantum properties of an object cannot be measured without being "unavoidably and irrevocably disturbed from their original state".[22] This means that if two communicators exchange messages with each other using the quantum properties of an object that they send between themselves (for example, the wave properties of a beam of light), there is a guarantee that any method used to intercept the message would be detectable. Therefore, in theory, quantum technology can provide communications systems that would be completely secure against any current or future interception technologies.[23]

13. Prototype quantum communications systems have already been used in real-world applications, for example in the Geneva Canton elections of 2007 and at the 2010 FIFA World Cup.[24] These involved short-range communication over dedicated connections between two pre-determined points. Goals for the quantum communications community now include:

- reducing the cost, size and power consumption of the devices needed for quantum communication;
- integrating quantum communications technologies into existing telecommunications devices;
- developing networks of quantum communication systems; and
- developing systems that can communicate over open space rather than through optical fibre.[25]

20 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), pp29–36
21 Q136
22 UK Quantum Technology Hub, 'Annual Report 2014–15' (2015), p6
23 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p50
24 'Quantum cryptography to protect Swiss election', New Scientist and 'Durban's high tech stadium', FIFA, both accessed 20 July 2018
25 Quantum Communications Hub (QUT0009) and Quantum Communications Hub, 'Annual Report 2016–17' (2017)

Quantum computing

14. Conventional computers store and process information using vast numbers of components that can each be in one of two states, usually labelled as '1' or '0' (or alternatively 'on' or 'off'). These components are typically simple electronic devices, often just several thousandths of the width of a human hair in size,[26] with each one storing one piece, or 'bit', of information. Quantum computers exploit quantum effects to replace these 'bits' with 'qubits', which can each exist in a combination of '0' and '1' simultaneously (a 'qubit' is just a bit that exhibits quantum behaviour). The ability of qubits to be in multiple states at once means that a quantum computer can try large numbers of solutions to a problem simultaneously, offering enormous reductions in computing times for certain kinds of calculations. For example, whereas a conventional computer would take millions of years to work through all the possible combinations of a digital 'key' to access secured information, a quantum computer could try them all at once and arrive at the solution in a few seconds.[27] Emphasising this point, Professor Ian Walmsley, Director of the Networked Quantum Information Technologies Hub, told us that the "quantum computer is as different from the modern-day computer as the modern computer is from the abacus".[28]

15. As described above, quantum computers offer radically improved performance over conventional computers for solving certain kinds of problems. Some of the anticipated applications for this capability include:

- simulating chemical behaviour to enhance drug or materials discovery;[29]
- optimising logistical arrangements, such as task allocation in the NHS or the management of supply chains;[30] and
- increasing the speed and capacity of data analysis, enabling improvements in artificial intelligence.[31]

The Networked Quantum Information Technologies Hub told us that many of these potential applications are "speculative", but that "history suggests that disruptive technology indeed creates new products and services that are socially desirable".[32] Professor Winfried Hensinger, of the University of Sussex, similarly told us that "it is very unlikely that we fully understand all the opportunities quantum computers pose" but drew comparisons to the unknown applications of conventional computers when they were first built.[33] Despite the uncertainty surrounding the ultimate uses of quantum computers, Jonathan Flint, President-Elect of the Institute of Physics, described them as "rightly the poster child" of quantum technologies due to the "huge implications" if successfully developed.[34]

26 The steady miniaturisation of these components over the last 50 years has driven 'Moore's Law', the observation that the number of them on a computer chip doubles every two years, with commensurate exponential improvement in computing capability over time. However, this progress is expected to end soon, as the components reach the fundamental size limit of a single atom. Quantum computers are hoped to be able to continue improvements in computing capability.

27 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p16

28 Q225

29 UCL Quantum Science and Technology Institute (QUT0008), para 5

30 Manchester Metropolitan University (QUT0003), para 13

31 Royal Academy of Engineering (QUT0012)

32 Networked Quantum Information Technologies Hub (QUT0006), para 13.2

33 Q228

34 Q79

Technological readiness

16. In 2015, the National Quantum Technologies Programme's Strategic Advisory Board published a roadmap for quantum technology development, which estimated the commercialisation of different application areas over timescales ranging from within five to over 20 years.[35] Although the different quantum technologies and application areas are at different stages of development, the University of Strathclyde told us that in broad terms, society stands "on the cusp" of a second "quantum revolution".[36] The UCL Quantum Science and Technology Institute similarly told us that quantum technologies are "currently undergoing a profound transition, as the field's balance starts to shift from [being] academically-driven towards commercial-driven research […] where systems integration and engineering are the key challenges".[37] Teledyne e2v noted, however, that these challenges will take time to overcome, cautioning that:

> Although there are very encouraging demonstrations of future capabilities it is true that in many areas there is much more to be done to reach the delivery of real products and services with superior performance exceeding that of incumbent solutions.[38]

17. Quantum computers are widely considered to be the quantum technology furthest from market,[39] although Professor John Morton, of University College London, noted that progress on this front had recently been made quicker than expected.[40] Professor Walmsley told us that early-stage, very small-scale quantum computers already existed, but that "there is a very wide range of opinions" on when a fully scalable quantum computer will be available; he estimated that "it will be five to ten years before the next generation of real computers begins to emerge".[41] Professor Morton told us that the development of a quantum computer "able to solve a problem that the world's fastest super-computer cannot solve" is expected by 2019, but clarified that "it will not be a useful [problem], and we expect it to stimulate a lot of work over the next, say, three years to find useful problems that such computers can solve".[42]

18. Although the market opportunity for quantum technologies lies predominantly in the future, we heard that business investment and procurement was already taking place. Professor Trevor Cross, Chief Technology Officer at Teledyne e2v, told us that his company had started taking orders for quantum technology components,[43] while M Squared told us that "the first commercial outcomes from our portfolio of Innovate UK programmes are

35 National Quantum Technologies Programme Strategic Advisory Board, 'A roadmap for quantum technologies in the UK' (2015)
36 University of Strathclyde (QUT0004)
37 UCL Quantum Science and Technology Institute (QUT0008), para 19
38 Teledyne e2v (QUT0016); A review of the development timescales of various technologies found that the time taken for market deployment and commercialisation is often comparable or even greater than the time taken for invention, development and demonstration—Gross *et al.*, 'How long does innovation and commercialisation in the energy sectors take? Historical case studies of the timescale from invention to widespread commercialisation in energy supply and end use technology', Energy Policy vol 123 (2018)
39 For example, see: UCL Quantum Science and Technology Institute (QUT0008), para 23; Quantum Technology Hub for Sensors and Metrology (QUT0013); and Professor Sir Peter Knight (QUT0015)
40 Q80
41 Q227; this broadly tallies with UK Quantum National Technologies Programme, 'A roadmap for quantum technologies in the UK' (2015) and written evidence from Dr Ashley Montanaro *et al.* (QUT0005), para 7 and the UCL Quantum Science and Technology Institute (QUT0008), para 23 but Dstl has published a more conservative estimate of after 2030—Dstl, 'UK Quantum Technology Landscape 2016' (2016)
42 Q80
43 Q293

now being offered to existing customers".[44] Airbus told us that the potential of quantum technologies to help them deliver "greater performing, more efficient and environmentally friendly aircraft" had led them to establish a Quantum Technology Application Centre at its facility in South Wales.[45] The University of Bristol told us that for every £1 invested in their Quantum Engineering Technology Labs, companies spun out from the centre had already raised £1.70.[46]

The National Quantum Technologies Programme

19. In the 2013 Autumn Statement, the Government announced an investment of £270m over five years into a National Quantum Technologies Programme, "to support translation of the UK's world leading quantum research into application and new industries".[47] As part of this programme, the Engineering and Physical Sciences Research Council invested £120m into a national network of four new Quantum Technology Hubs, each spread over multiple universities in the UK.[48] The four Hubs were tasked with "tackling the key technological challenges that need to be overcome to realise the promise of quantum technologies",[49] and covered the four application areas outlined in paragraphs 9 to 15 of this Report: sensors and metrology; imaging; communications; and networked information technology. In addition to the Hubs, the programme has provided:

- £50m for innovation, including industry-led feasibility studies, collaborative research and development projects and the creation of a cross-sectoral Quantum Technologies Special Interest Group, which aims to explore market opportunities and build UK supply chains;
- £49m for training and skills, which has enabled the establishment of three Centres for Doctoral Training in quantum technology and three Training and Skills Hubs in quantum systems engineering;
- £30m for quantum technology demonstrator projects overseen by the Defence Science and Technology Laboratory, in areas such as gravity imaging and quantum navigation;
- £29m to establish a Quantum Metrology Institute, based at the National Physical Laboratory, to provide the measurement expertise and facilities needed to develop quantum technologies; and
- £16.5m for Quantum Technologies Fellowships, awarded to 14 key researchers and their teams to address the challenges of translating quantum science through technology to eventual application, as well as develop their own skills and careers.[50]

44 M Squared (QUT0024)
45 Airbus (QUT0001)
46 QET Labs, University of Bristol (QUT0019), para 6
47 HM Treasury, 'Autumn Statement 2013' (2013), para 1.210
48 UK National Quantum Technologies Programme, 'UKNQT Hubs', accessed 11 July 2018
49 National Quantum Technologies Programme, 'Delivering the National Strategy for Quantum Technologies' (2016), p3
50 UK Research and Innovation (QUT0023), Annex 1 and National Quantum Technologies Programme, 'Delivering the National Strategy for Quantum Technologies' (2016), p2

20. The National Programme is overseen by a Strategic Advisory Board comprising representatives from academia, industry, Government and the four hubs.[51] This Board published a national strategy for quantum technologies in 2015, which set out five key aims:

- enabling a strong foundation of capability in the UK;
- stimulating applications and market opportunity in the UK;
- growing a skilled UK workforce;
- creating the right social and regulatory context; and
- maximising benefit to the UK through international engagement.[52]

Despite the five-year duration of the initial funding from Government, the strategy set out action required over a 20-year period.

21. With the initial funding for the National Quantum Technologies Programme due to end in 2019,[53] we heard that the programme had achieved broad success and placed the UK's quantum technology sector in a world-leading position.[54] Jonathan Flint, President-Elect of the Institute of Physics, told us that of the many academic and industrial collaboration programmes he had been involved in "the quantum programme is one of the best, it is certainly the most productive".[55]

22. The Programme has so far involved at least 225 companies and attracted around £130m of external funding, over £36m of which has come from the private sector.[56] Professor Knight, who sits on the National Programme's Strategic Advisory Board, suggested that the programme's success was demonstrated by the similar efforts other countries were now planning.[57] UK Research and Innovation told us that "the first phase of the National Programme has exceeded expectations in turning [the UK's] scientific strengths into early stage technologies".[58] The main criticisms of the National Programme related to the lack of progress that some, such as Teledyne e2v, felt had been achieved on recommendations made for the Programme by the Government Office for Science in 2016.[59] The main recommendations for which a lack of progress was highlighted included:

- confirmation of the National Programme's continuation beyond 2019;

51 'Strategic Advisory Board', National Quantum Technologies Programme, accessed 9 October 2018
52 National Quantum Technologies Programme Strategic Advisory Board, 'National Strategy for Quantum Technologies' (2015), p4
53 UK Research and Innovation (QUT0023), para 2
54 For example, see: Airbus (QUT0001); QuantIC (QUT0002), paras 6 and 21; Networked Quantum Information Technologies Hub (QUT0006), para 3; University of Sussex (QUT0007), para 5.2; Professor Sir Peter Knight (QUT0015); Fraunhofer UK Research Ltd (QUT0021), section 3; Ministry of Defence (QUT0026), para 4; Q182
55 Q83
56 Professor Sir Peter Knight (QUT0015); Q356
57 Q52; programmes similar to the UK's National Quantum Technologies Programme have been proposed or initiated in the USA, the EU and Canada—US Congress, House of Representatives Bill 6227, 'National Quantum Initiative Act' (2018); EU Quantum Flagship, 'Quantum Technologies Flagship Final Report' (2017) and 'Quantum Canada', National Research Council Canada, accessed 10 October 2018
58 UK Research and Innovation (QUT0023), para 6
59 For example, see: QuantIC (QUT0002), para 5; Institute of Physics (QUT0010), para 3; Teledyne e2v (QUT0016); Qq51 and 311–312

- the establishment of 'Innovation Centres' to drive the commercialisation of quantum technologies; and
- the creation of a new body to co-ordinate the Programme's different activities "more effectively".[60]

Professor Delpy explained that, for those recommendations that could not be rapidly addressed, the National Programme's Strategic Advisory Board had drawn up plans for future action, but that delivering upon these plans would be dependent upon continuation of the National Programme.[61]

Continuing the National Programme

23. In keeping with the Government Office for Science's recommendation to continue the National Quantum Technologies Programme, Professor Delpy told us that the Programme's Strategic Advisory Board had submitted a bid to the Government setting out plans for a second phase of the National Programme.[62] Professor Knight explained that the priorities for this second phase would be to support "the skill base, the research base and the Innovation Centres".[63] The funding required for the bid was estimated to be around £338m.[64]

24. We heard a great deal of support for continuation of the National Programme from across the quantum technologies community, with a variety of arguments for its continuation offered.[65] The quantum technology community also made clear the urgency with which a decision on the programme's future was required.[66] We therefore wrote to the Chancellor of the Exchequer in July and September 2018, outlining our support for a second phase of the National Quantum Technologies Programme and urging the Government to make a decision on the Strategic Advisory Board's bid as soon as possible.[67]

25. Responding to our letter from July 2018, the Chancellor announced in September 2018 the allocation of an £80m extension to funding for the National Quantum Technology Hubs, subject to business case approval.[68] Professor Sir Mark Walport, Chief Executive of UKRI, explained that this meant that the Hubs were "essentially being funded at a

60 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), pp9–14
61 Q51
62 Qq25–26
63 Q30
64 Q30
65 See, for example: QuantIC (QUT0002), para 6; University of Strathclyde (QUT0004); Networked Quantum Information Technologies Hub (QUT0006), para 3; University of Sussex (QUT0007), para 1; UCL Quantum Science and Technology Institute (QUT0008), para 1; Quantum Communications Hub (QUT0009); Institute of Physics (QUT0010), para 7; Quantum Technology Hub for Sensors and Metrology (QUT0013); Teledyne e2v (QUT0016) and National Physical Laboratory (QUT0017), para 10. The arguments for continuation included: the opportunity for economic and social benefit; the benefit for national security as well as prosperity; the wide applicability of quantum technologies to other technologies and different sectors; the connection with the photonics industry, a current UK strength; and the UK's world-leading position on quantum technologies.
66 For example, see: University of Sussex (QUT0007), para 7.1; Quantum Communications Hub (QUT0009); Institute of Physics (QUT0010), para 7; Qq25–26, 163–164 and 249–250
67 Letter from Rt Hon Norman Lamb MP to Rt Hon Philip Hammond MP, 18 July 2018; letter from Rt Hon Norman Lamb MP to Rt Hon Philip Hammond MP, 12 September 2018
68 Letter from Rt Hon Philip Hammond MP to Rt Hon Norman Lamb MP, 6 September 2018

continuation of the level they had before".[69] He clarified that the business case consideration was "routine for an investment of this scale" and would "be done well in time for the putative start of the next programme".[70] The 2018 Budget subsequently announced:

> The Government will invest a further £235m to support the development and commercialisation of quantum technologies, including up to £70m from the Industrial Strategy Challenge Fund, and £35m to support a new national quantum computing centre.[71]

This money will also support "a new training and skills package".[72] Prior to us writing, the Government had already allocated £20m for a quantum technologies 'pioneer fund' to "support the development of between three and five prototype quantum-enabled devices", as well as £15m of capital investment to allow the Hubs to purchase new equipment.[73] Overall, this takes funding for the second phase of the National Quantum Technologies Programme to £315m, not far short of the £338m that the Programme's Strategic Advisory Board had estimated was required to complete a second phase.

26. **Quantum technologies offer the potential for significant economic growth and improved capabilities across multiple industry sectors. The first phase of the National Quantum Technologies Programme has placed the UK in a world-leading position. The Government announced £235m of funding for quantum technologies in the 2018 Budget, taking total funding for the next phase of the National Quantum Technologies Programme to £315m. We welcome the Government's decision to support a second phase of the National Quantum Technologies Programme with this funding, which is broadly commensurate with the Strategic Advisory Board's estimated requirements.**

69 Q375
70 Q357
71 HM Treasury, 'Budget 2018' (2018), para 4.20
72 'New funding puts UK at the forefront of cutting edge quantum technologies', Department for Business, Energy and Industrial Strategy and Department for Digital, Culture, Media and Sport, accessed 2 November 2018
73 UK Research and Innovation (QUT0031); 'UK to lead second revolution in quantum technologies', UK Research and Innovation, accessed 24 October 2018

3 Continuing the National Programme—Governance

27. The first phase of the National Quantum Technologies Programme has been overseen by a Strategic Advisory Board.[74] In its 2016 report on quantum technologies, the Government Office for Science recommended the establishment instead of "a body with the funding and sole remit to coordinate activities across the programme more effectively".[75] It suggested that this body "could help to prioritise spending and resources; respond to national and international developments; link government horizon-scanning to projects, competitions and demonstrators; and co-ordinate the purchase of scientific equipment".[76] Professor Sir Peter Knight, who co-authored the Government Office for Science report, explained that:

> We wanted to make sure that our partners could be part of a common board, so that they could work out a strategic investment system whereby they could see alignment of where their money could go […] What we now want, with the opportunities that UKRI has, is to have an investment strategy with that common board.[77]

28. Although the progress achieved by the existing Strategic Advisory Board was recognised,[78] we heard strong support from the quantum technology community for the establishment of a new body with expanded membership, remit, power and accountability.[79] Professor Trevor Cross, who sits on the current Strategic Advisory Board, told us that "it is going to be absolutely critical to set up the governance of the future programme in a different way, with executive powers", explaining that the current Board was "very much advisory and it does some good, but it does not have authority".[80] Dr Peter Thompson, CEO of the National Physical Laboratory, added that the establishment of a new Executive Board would also accelerate progress in the National Quantum Technologies Programme, in particular with regard to the Government Office for Science's 2016 recommendations, by providing a "single point of accountability".[81]

29. One of the main hopes for a new board was for greater co-ordination across the different activities of the National Programme. Professor Knight told us that the Strategic Advisory Board had already aimed to ensure that the first phase of the National Programme had "a coherence to it", with the different strands co-ordinated to support the development of quantum computers but also acting to exploit any opportunities that the intermediate technology developments offered along that route.[82] Indeed, some witnesses, such as the Networked Quantum Information Technologies Hub and the National Physical Laboratory, identified the coherence of the first phase of the National Programme as one of the distinguishing features of the UK quantum technologies 'ecosystem' compared

74 'Strategic Advisory Board', National Quantum Technologies Programme, accessed 12 November 2018
75 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p14
76 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p60
77 Q47
78 University of Sussex (QUT0007), para 6.1
79 See, for example: UCL Quantum Science and Technology Institute (QUT0008), para 7; Quantum Technology Hub for Sensors and Metrology (QUT0013); National Physical Laboratory (QUT0017), para 33; Qq159, 255–256 and 305
80 Qq285 and 305
81 Q312
82 Q5

to those of other countries.[83] However, many emphasised the scope for improved co-ordination.[84] In particular, the co-ordination between the academically-focused and translational strands of the Programme was highlighted as an element to improve. Dr Andrew Shields, Quantum Technologies Research and Development Lead for Toshiba Research Europe Ltd, called for "a much better-integrated programme, which integrates academia, industry and Government partners", as:

> In phase one, we really had two programmes: the [Engineering and Physical Sciences Research Council's] academic programme and the Innovate UK programme for industry. They have not been joined up all that much actually; they have had very different scales, as we have mentioned. They had very different timescales as well—the academic programme has been a five-year programme, whereas the industry projects have typically been a year or 18 months.[85]

30. The funding for the next phase of the National Quantum Technologies Programme has been awarded in several tranches and through different mechanisms.[86] Professor Sir Mark Walport, Chief Executive of UK Research and Innovation, explained that although the Strategic Advisory Board's bid for the second phase was "a single overall ask, it was in a series of different buckets".[87] In addition to this fragmented decision-making process, Professor Ian Walmsley, Director of the Networked Quantum Information Technologies Hub, noted that the second phase of the National Programme would oversee a broader range of activities than the first phase, adding to the need for greater co-ordination.[88]

31. **Although the first phase of the National Quantum Technologies Programme is widely seen to have been successful, we believe that there is room for improvement in the co-ordination across the Programme as it moves into a second phase, in particular between its more academically-focused and its more commercially-focused activities.**

Representation

32. The National Programme's current Strategic Advisory Board comprises representatives from academia, industry, funding councils and the Government.[89] However, several witnesses, including Professor Trevor Cross of Teledyne e2v and Professor Sir Michael Pepper of the Royal Academy of Engineering, argued that industry should have a stronger role in directing the next phase of the National Programme.[90] QuantIC, the Hub for

83 QuantIC (QUT0002), para 21; Networked Quantum Information Technologies Hub (QUT0006), para 7.2; Quantum Technology Hub for Sensors and Metrology (QUT0013); National Physical Laboratory (QUT0017), para 42; M Squared (QUT0024)

84 See, for example: UCL Quantum Science and Technology Institute (QUT0008), para 7; Institute of Physics (QUT0010), para 4; Quantum Technology Hub for Sensors and Metrology (QUT0013); Teledyne e2v (QUT0016); QET Labs (QUT0019), para 18; Qq255, 283–284

85 Q283; Professor Trevor Cross, who sits on the national programme's Strategic Advisory Board, said he agreed "totally"—Q283

86 The £315m funding for the National Programme has been awarded through: the £20m Pioneer Fund, announced in the Industrial Strategy White Paper; £80m for continuation of the Hubs, announced on 6 September 2018; and announcements in the 2018 Budget, some of which will be delivered through future waves of the Industrial Strategy Challenge Fund.

87 Q375

88 Q255

89 'The Quantum Technologies Strategic Advisory Board Membership', National Quantum Technologies Programme, accessed 5 November 2018

90 For example, see: Quantum Technology Hub for Sensors and Metrology (QUT0013); Qq18, 77, 285, 304–305

quantum-enhanced imaging, told us that industry input into the direction of the National Programme would grow increasingly important as the programme's focus turned more explicitly towards commercialisation of quantum technologies.[91] The Quantum Technology Hub for Sensors and Metrology added that if industry was to provide an increased proportion of the funding for the second phase of the National Programme, which the Government had said would be required,[92] then it would expect increased influence over the direction of the programme.[93] Professor Cross agreed, saying that industry would want collective influence over research that targeted specific commercial application, which he thought should make up about 60% of the second phase of the National Programme.[94] Indeed, Sam Gyimah MP, Minister of State for Universities, Science, Research and Innovation, agreed that "if commercialisation or capturing economic benefit is key, having industry help to drive that decision is particularly relevant to success".[95]

33. The Royal Academy of Engineering noted the importance also of "collaboration between UK industry, research and the regulatory bodies […] for the UK to gain a competitive advantage by leading the development of global standards".[96] Dr Thompson similarly told us that it was "absolutely critical" that standards bodies "work with industry to shape the standards to enable UK industry to succeed in future".[97] Professor David Delpy, Chair of the National Programme's Strategic Advisory Board, explained that the standardisation of components was "the difference between quantum science and a real quantum industry".[98]

34. Many quantum technologies are 'dual-use', meaning that they have military and civil applications. The potential military applications of quantum technologies, and the consequent importance of these technologies to the UK's defence capabilities, are discussed further in paragraphs 101 to 107 of this Report. In addition to making the direction and progress of the UK quantum industry relevant to national security as well as national prosperity, this also has implications for academics and companies working on quantum technologies. For example, the Institute of Physics explained that:

> Dual-use status may impose restrictions on the trade of some quantum technologies—in particular, the US International Traffic in Arms Regulations (ITAR) place strict limitations on the use of US-developed defence-related knowledge and technology, including those of relevance to quantum technologies […] Training in the issues associated with both US and UK export controls for dual-use technologies has been delivered through the [National Quantum Technologies Programme] to mitigate potential risks, and should be continued as part of any future programme.[99]

91 QuantIC (QUT0002), para 8
92 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p10; Qq356, 360 and 373
93 Quantum Technology Hub for Sensors and Metrology (QUT0013)
94 Qq285 and 305
95 Q369
96 Royal Academy of Engineering (QUT0012); see also Institute of Physics (QUT0010), para 15; QET Labs, at the University of Bristol, similarly told us that "effective communication and collaboration is required between all related regulatory bodies, academia and industry in order to avoid unnecessary barriers to the development of the industry"—QET Labs, University of Bristol (QUT0019), para 27
97 Q317
98 Q5
99 Institute of Physics (QUT0010), para 30

The Ministry of Defence told us that it "maintains a keen awareness of developments" in quantum technologies through its close relationship with the National Quantum Technologies Programme.[100] The Networked Quantum Information Technologies Hub similarly told us that "the current governance of the National Quantum Technologies Programme includes advisors from the Defence Science and Technology Laboratory and the Government Communications Headquarters among others to whom we look to help recognise [matters arising from the dual-use nature of quantum technologies] and their implications on the actions within the Hub".[101] However, the University of Sussex suggested that:

> Bolstering the participation of the Defence Science and Technology Laboratory in the National Quantum Technology Hubs will help addressing the challenges arising from dual-use applications at the early stage in their development.[102]

35. **The governing body of the second phase of the National Quantum Technologies Programme should engage with, and seek guidance from, academia, industry, regulators, standards bodies and Government bodies overseeing national security and defence. Industry should have a strong collective influence on the decisions of the governing body, in keeping with the increased role and investment expected of industry as quantum technologies achieve market readiness.**

Structure

36. Professor David Delpy, Chair of the National Quantum Technology Programme's current Strategic Advisory Board, outlined how he thought the new board should be set up and operate:

> We need a high-level executive board, possibly even a director, but I would not want to see that embedded in Government. The whole advantage of this programme is that it is a mix of industry, academia, Government Departments and other institutions that have worked extremely well together. They have found a way of working and it would be nice to keep it outside, rather than embedding it within UK Research and Innovation, the Department for Business, Energy and Industrial Strategy or some other Government Department.[103]

He suggested the Energy Technologies Institute as one example that a new board could build upon.[104] The Energy Technologies Institute is a public-private partnership between global energy and engineering companies and the UK Government, with a board made up of representatives from both.[105]

100 Ministry of Defence (QUT0029), para 4
101 Networked Quantum Information Technologies Hub (QUT0006), para 12.1
102 University of Sussex (QUT0007), para 10.3
103 Q67
104 Q48
105 'About the ETI', Energy Technologies Institute, accessed 9 November 2018

37. Professor Sir Mark Walport told us that a challenge director had been appointed for the quantum technologies challenge, who would "be working very closely with the advisory board for the quantum technologies".[106] Sir Mark indicated that this was one part of an ongoing process to bring the National Quantum Technologies Programme under a "single governance model".[107] However, the Science Minister told us that the "situation is evolving" and that the final governance model of the programme had not yet been decided.[108]

38. **We have heard strong support from across the UK quantum technologies community for the establishment of a new governance structure for the second phase of the National Quantum Technologies Programme.** ***The Government should establish a new Executive Board to oversee the second phase of the National Quantum Technologies Programme within three months of this Report's publication. The new Board should have the power to make decisions over the delivery of the second phase of the National Programme, and a corresponding level of control over the funding allocated to the next phase of the National Programme. It should have a clearly defined mission statement and be held accountable for delivering on it. The mission statement should include an overall aim to support the development of a UK quantum technologies industry that delivers the maximum economic, national security and societal benefit for the UK public as a whole. The new Board should comprise representatives from academia, small and medium-sized enterprises, large companies, standards bodies, regulators and the Government, including from national security and defence organisations.***

Strategy

39. During the course of our inquiry, several witnesses referred to the benefits of conducting a review of the current quantum technologies 'ecosystem', or of assessing the specific market opportunities for quantum technologies and what would be required to realise these opportunities.[109] The Institute of Physics, for example, suggested that a "review of the landscape" would help to identify "emerging areas" that had not been included under the scope of the first phase of the National Programme, but which might now "benefit from access to programmatic support and strategic alignment".[110] Teledyne e2v told us that "future investments should mainly be targeted towards specific market and customer needs", which could be identified through reviews of market opportunities:

> Rigorous market assessments must be undertaken and shared within the UK community, to ensure that technologies are directed towards genuine market needs. Proposals for investment should be reviewed by experts in that market—for example for medical applications: medical practitioners, clinical scientists and industry technologists.[111]

106 Q399
107 Q399
108 Q405
109 For example, see: Institute of Physics (QUT0010), para 22; Teledyne e2v (QUT0016); M Squared (QUT0024); Qq46, 184–185 and 305
110 Institute of Physics (QUT0010), para 22
111 Teledyne e2v (QUT0016)

Dr Andrew Shields, Quantum Technologies R&D Lead at Toshiba Research Europe Ltd, similarly recommended "a national roadmap that details when the applications [for quantum technologies] will be realised and how the technology has to evolve to meet those applications".[112] Such a roadmap could additionally assess the infrastructure and skills that would be needed to meet targeted applications.[113]

40. In addition to the benefits of a roadmap for planning and co-ordinating the National Programme, M Squared, a photonic and quantum technology developer, suggested that a similar "system of benchmarking" would be "of great advantage to the UK government, academics and industry leaders".[114] M Squared's CEO, Dr Graeme Malcolm, explained that such a system should serve to "give everybody, including the industry and the hubs, some sort of dashboard of how we are doing".[115] This would also provide a way to monitor the progress of the second phase of the National Programme.

41. The Strategic Advisory Board published a brief roadmap of future quantum technology markets in 2015, and some individual Hubs were working on roadmaps specific to their sector.[116] However, it appears that a detailed roadmap covering all potential applications and markets for quantum technologies is not currently developed. Professor Delpy contrasted the situation for quantum technologies with those of more established industries:

> If we had a sector council, as there is in automotive, there would be a 20-year roadmap that would identify a series of demonstrators that we need, as Rolls-Royce has for 50 years. In this area, where we are developing an industry, we do not have roadmaps of the same precision.[117]

The Science Minister informed us that the Department for Business, Energy and Industrial Strategy and the Department for Digital, Media, Culture and Sport were jointly conducting a review of quantum technologies, which would "look at what support is necessary to realise the commercial benefits and support responsible development".[118] It is not clear to what extent this could contribute to the development of a roadmap for the future development of the UK quantum technologies industry.

42. ***The Executive Board should produce a detailed roadmap, or series of roadmaps, for the future potential markets for quantum technologies in the UK, in consultation with appropriate experts from the market sectors identified. The roadmap should assess the likely size and timeframe of each potential market, as well as the technological developments, infrastructure, workforce, supply chains and regulatory measures that are expected to be required to harness each market opportunity. The roadmap should cover the next twenty years and be updated annually. It should be publicly available, with a first iteration completed within one year of this Report's publication.***

112 Q305
113 Institute of Physics (QUT0010), para 20; Q185
114 M Squared (QUT0024)
115 Q184
116 National Quantum Technologies Programme Strategic Advisory Board, 'A roadmap for quantum technologies in the UK' (2015) and, for example, Networked Quantum Information Technologies Hub, 'Technical Roadmap for Fault-Tolerant Quantum Computing' (2016)
117 Q46
118 Q382

43. ***The Executive Board should use the roadmap(s) of future quantum technology markets to identify potential obstacles to the development and commercialisation of quantum technologies in the UK and to define a strategy to overcome these. The strategy should be published and updated alongside the roadmap and include clear, measurable milestones, to be reviewed annually.***

4 Continuing the National Programme—Innovation Centres

44. One of the main recommendations made by the Government Office for Science for the National Quantum Technologies Programme was to establish 'Innovation Centres' to "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".[119] Professor Sir Peter Knight, who co-authored the Government Office for Science's report, expanded upon their planned role:

> The Innovation Centres are fulfilling a need that industry has for specialist facilities. Currently, the smaller companies may not have those. If the bigger companies have them, they do not have the time to invest in them [… The Centres] will be a single place where industry can come to test some of the demonstrators that have already started to come out of the existing phase 1 programme […] The Innovation Centres will bring together in one place the industrial users—the people who have the application—the researchers who developed the original lab-scale proof-of-principle demonstrators and, ideally, the skilled workers who are coming through both the skills hubs and the Centres for Doctoral Training.[120]

Professor John Morton, Director of the UCL Quantum Science and Technology Institute, described a similar role for what he wanted to see from the Innovation Centres.[121]

45. We heard wide support for the establishment of Innovation Centres, with a range of benefits that they could deliver identified by witnesses including the Institute of Physics and BT.[122] Several witnesses shared Professor Knight's vision that Innovation Centres could provide the shared facilities required by industry (such as manufacturing, testing and validation equipment),[123] as well as representing physical focal points bringing together researchers, innovators, businesses, a skilled workforce and others, and around which supply chains could consolidate.[124] BT told us that Innovation Centres should additionally provide market analysis and business support services to those trying to develop finished commercial products.[125] Professor Ian Walmsley, Director of the Networked Quantum Information Technologies Hub, added that Innovation Centres could support innovative start-up companies by acting as a client for intermediate technologies:

119 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p13
120 Q41
121 Qq99–100
122 For example, see: QuantIC (QUT0002), paras 22–23; Networked Quantum Information Technologies Hub (QUT0006), para 3; UCL Quantum Science and Technology Institute (QUT0008), para 6; Institute of Physics (QUT0010), para 12; Quantum Technology Hub for Sensors and Metrology (QUT0013); Teledyne e2v (QUT0016); UK Diamond Quantum Technology Community Informal Group (QUT0025); BT Group (QUT0032), para 1; Qq260 and 288
123 QuantIC (QUT0002), para 23; Qq100 and 211
124 QuantIC (QUT0002), para 22; Institute of Physics (QUT0010), para 12; Quantum Technology Hub for Sensors and Metrology (QUT0013); BT Group (QUT0032), para 4; Q41
125 BT Group (QUT0032), para 6

> How do [start-up] companies find a business model for an instrument or a machine that is still 10 years in the future? For us, part of the answer is that if there is a national centre for quantum computing—one of these innovation centres where such a device is built—it becomes a business model for both the hardware and software companies to be involved.[126]

46. QuantIC, the national Hub for quantum-enhanced imaging, told us that "integration of the Hubs with Innovation Centres is essential to avoid the creation of artificial barriers in the technology development and innovation pipeline".[127] Professor Tim Spiller, Director of the Quantum Communications Hub, similarly warned that the separate roles of the existing Hubs and any new Innovation Centres might hinder the development of quantum technologies through to commercial application:

> I have two cautionary issues with separate Innovation Centres. The first one is that I remember when Innovate UK was called the Technology Strategy Board and they focused on the very high technology levels and the Engineering and Physical Sciences Research Council focused on the very low ones and there was a big gap in the middle. I am afraid that if we have Innovation Centres and Hubs that are focused on research and innovation, there is a danger of that gap […] The other issue with separate [Hubs and Centres] is that you have many interface points where you do tech transfer between a Hub or an academic group and an Innovation Centre and someone has to manage all of those transfer points if there are going to be separate entities.[128]

QuantIC's Programme Manager, Dr Sara Diegoli, agreed that Professor Spiller's concerns were legitimate, but told us that "if the Hubs are maintained in the current translational role and they are not moved in their remit towards the science basis, that interface could be made to work between the Hubs and the Innovation Centres".[129] Professor Spiller indicated that the National Programme could overcome the potential challenges he had identified, but that it would require co-ordination and alertness to the problem.[130] Professor Kai Bongs, Director of the Quantum Technology Hub for Sensors and Metrology, outlined a similar vision:

> What is very, very important is that [Innovation Centres] enable smooth links between the academic-funded programme of the quantum Hubs and the industry side […] so that they fill in gaps and we have intrinsically interlinked participation from both the industry and the academic sides, which could be by personnel or by co-location.[131]

126 Q271
127 QuantIC (QUT0002)
128 Qq147–149
129 Q150
130 Qq148–149 and 159; Professor Walmsley similarly indicated that the addition of Innovation Centres to the National Quantum Technologies Programme was one reason why the Programme would benefit from a co-ordinating, executive governing body—Q255
131 Q242; the Networked Quantum Information Technologies Hub similarly told us that "the proposed continuation of the Technology Hubs and the creation of the new Innovation Centres should include close coordination between the two entities"—Networked Quantum Information Technologies Hub (QUT0006), para 10.4

47. Professor Cross told us that there was "an enduring logic" to the four application areas around which the Hubs were organised, and suggested that although there "might not be 100% alignment with the Hubs", "it is not a bad idea to think that you need [one or more Innovation Centres] in each of those spaces".[132] The point was made repeatedly, however, that end-users of quantum technologies cared only about the performance of a product using quantum technology, rather than the underlying technology.[133] In keeping with this, BT told us that Innovation Centres should be established to address specific industry sectors, rather than focusing on specific quantum technologies.[134] Dr Mark Bentall, Head of Technology Development and Innovation at Airbus Defence and Space, confirmed that "from a system integrator point of view, our focus is quite narrowly on our market".[135] Illustrating that multiple quantum technologies could offer useful applications in a single sector, BT told us that "there is already a line of sight to exploitation in the telecoms sector for quantum key distribution, quantum clocks and timing and quantum sensing solutions".[136] They acknowledged, however, that a sector-based approach may not be appropriate for less mature quantum technologies.[137]

48. Another point of discussion regarded where Innovation Centres should be sited. Although the importance of good co-ordination between the Hubs and the Innovation Centres was emphasised by many witnesses, Professor Knight clarified that "it should not be assumed that the Innovation Centres will be based at the Hubs".[138] Indeed, Teledyne e2v told us that it was their "firm opinion that some of these [Innovation] Centres should be located close to industry rather than as extensions of University activity and the current Hubs", as:

> In turning the science into products and services from which we can make money, a huge amount of intellectual property as well as manufacturing capability will come out of the industrial base. A lot of industries, and sometimes that includes small and medium-sized enterprises too, are more comfortable working with industrial partners, because the culture is much more driven towards getting those products produced in a way that can be sold and used.[139]

Professor Bongs agreed that there would be an advantage in Innovation Centres being located close to areas of existing manufacturing capability, in particular.[140] Professor Walmsley noted, however, that "the character of the Innovation Centres and the specific location could be quite different" across the different application areas that they targeted, highlighting in particular the long-term approach that would be required for quantum computing.[141] Indeed, the need for different Innovation Centres to play different roles and operate differently in different sectors was made clear to us throughout our inquiry.[142]

132 Q289
133 For example, see: Qq142, 147 and 188
134 BT Group (QUT0032), para 4
135 Q282
136 BT Group (QUT0032), para 5
137 BT Group (QUT0032), para 5
138 Q41
139 Teledyne e2v (QUT0016) and Q287
140 Q270
141 Qq246–247
142 For example, see: Qq100, 152, 154, 242, 246, 270 and 290

49. UK Research and Innovation told us that "the establishment of Innovation Centres to provide shared resources for innovation in quantum technologies is a priority as we consider how we build on the first phase of the National Programme".[143] However, Professor Sir Mark Walport, Chief Executive of UKRI, clarified that the plans for Innovation Centres had evolved since they were first recommended in 2016, and argued that the focus should be on providing "environments where industry and academia can work together" rather than delivering new "bricks and mortar".[144]

50. The announcement of funding for the second phase of the National Quantum Technologies Programme in the 2018 Budget detailed only "£35m to support a new national quantum computing centre" and made no reference to Innovation Centres.[145] Professor Walport told us in September 2018 that UKRI was "very interested" to see what proposals for Innovation Centres would come forward from industry.[146] The Minister, Sam Gyimah MP, agreed and added that "we should leave space for industry to shape how the Innovation Centres, or whatever we call them, evolve".[147] Professor Walmsley, however, warned us that although the timing for decisions on the Innovation Centres was not "as critical as for the Hubs", their planning nevertheless "ought to move rapidly […] we need to be getting that on the agenda".[148]

51. **We agree with UK Research and Innovation that the establishment of Innovation Centres is a "priority" for the National Programme going forward. The announcements made confirming the extension of the National Quantum Technologies Programme into a second phase did not, however, reference Innovation Centres and proposed something comparable only in the quantum computing domain. Although the new quantum computing centre is welcome, it is worth noting that quantum computing is the quantum technology furthest from market. The drive to advance technologies from the existing Hubs towards greater market readiness—for example, through an Innovation Centre or Innovation Centres—would therefore appear to be most urgent for other quantum technologies.**

52. ***The second phase of the National Quantum Technologies Programme should establish Innovation Centres to provide access to facilities for developing, manufacturing, testing and validating quantum technologies, as well as to act as focal points around which collaboration and supply chains can consolidate. This will require Innovation Centres to exist, at least in part, as physical centres rather than as 'virtual networks'. Reflecting the need for Innovation Centres to focus on the development of commercial products, Innovation Centres should target specific market sectors rather than reflecting the different types of quantum technologies, although multiple sector-specific Innovation Centres could co-occupy sites where they require the same shared technical facilities. While we support the use of suitable existing infrastructure to house Innovation Centres where it can deliver what is required more quickly and at a reduced cost, this should not dilute the concept of Innovation Centres or weaken the drive to establish them as soon as possible. In its response to this Report, the Government should confirm its intention***

143 UK Research and Innovation (QUT0023), para 19
144 Q369
145 HM Treasury, 'Budget 2018' (2018), para 4.20; 'New funding puts UK at the forefront of cutting edge quantum technologies', Department for Business, Energy and Industrial Strategy and Department for Digital, Culture, Media and Sport, accessed 12 November 2018
146 Q369
147 Q369
148 Q248

to set up Innovation Centres and outline how many it intends to establish, which sectors they will cover and what the timeline is for their establishment. The Executive Board must ensure that there is good co-ordination between the new Innovation Centres and the Hubs and ensure that technologies are supported through research, development and commercialisation and to provide strategic oversight so that activities in Innovation Centres and Hubs complement each other.

Learning from the Catapult Centres

53. With a focus on developing technology-based economic opportunities through shared facilities and physical centres for convening relevant stakeholders, the proposed Innovation Centres share similarities with the 'Catapult Centres' that already exist (see footnote for description of Catapult Centres).[149] An independent review of the Catapult Centres concluded in 2017 that although "the concept of Catapults is sound" and the Centres had achieved some success, they could have delivered greater impact had they started with a clear statement of purpose, and been subject to stronger governance mechanisms, with clearer objectives, defined performance measures and more responsive decision-making.[150] It made several recommendations, including for:

- all Catapult Centres to draw up "robust, focused business plans supported by measurable milestone plans that will lead to economic benefits for the UK economy through addressing clearly articulated market failures";
- all Catapult Centres to improve governance and financial and performance management arrangements "so there can be ongoing monitoring and transparent evaluation to ensure value for money to the tax payer"; and
- any new Catapult Centres to address identifiable barriers to commercialisation, ensure that stakeholders from academia, industry and are willing to participate and set out viable core objectives.[151]

54. **The proposed Innovation Centres bear resemblance to the Catapult Centres that already exist.** ***The Government, UK Research and Innovation, and the new Executive Board of the National Quantum Technologies Programme should ensure that the planning of Innovation Centres incorporates lessons learned from the experience and assessment of the Catapult Centres. The Innovation Centres should have clear purpose statements, measurable objectives and be subject to periodic performance assessment.***

149 There are ten sector-specific Catapult Centres, administered by Innovate UK to "transform the UK's capability for innovation"; they are physical centres providing a focal point for businesses, scientists and engineers as well as access to expert technical capabilities, equipment, and other resources for supporting innovation—'About Catapult', Innovate UK, accessed 8 November 2018

150 Ernst & Young LLP, 'UK SBS PS17086 Catapult Network Review' (2017)

151 Ernst & Young LLP, 'UK SBS PS17086 Catapult Network Review' (2017), pp14–15

The national quantum computing centre

55. As already mentioned, the funding for the second phase of the National Quantum Technologies Programme included £35m for the establishment of a new national quantum computing centre, which appears to be comparable to an Innovation Centre in this field.[152] Professor Ian Walmsley, Director of the Networked Quantum Information Technologies Hub, advocated such a centre as part of a national effort to build a quantum computer:

> This is an area that is analogous to a moon shot: a once-in-a-lifetime opportunity to put the UK right at the forefront […] It is an area where significant new investment could reap very important and broad long-term rewards. That will involve not just academic institutions but Government centres that will be the places where quantum computers exist, much as the early-stage [conventional] computers did. Most importantly, it is an opportunity for new-stage companies to build the engineering expertise that is needed to drive this technology, both in hardware and, importantly, in software. The co-location of that hardware and software development seems to us to be a real opportunity for the nation.[153]

The importance of developing software as well as hardware for a quantum computer was raised by other witnesses,[154] with Dr Ashley Montanaro, of the University of Bristol, telling us that this aspect had been "under-represented" in the first phase of the National Programme.[155]

56. **We welcome the Government's decision to fund a new national centre for quantum computing. *The new national quantum computing centre should focus on the development of software for quantum computers as well as hardware.***

152 HM Treasury, 'Budget 2018' (2018), para 4.20; see also Q271
153 Q231; see also Qq246–247
154 Dr Ashley Montanaro *et al.* (QUT0005); Q83–84
155 Q83

5 Continuing the National Programme—Funding

57. The second phase of the National Quantum Technologies Programme was allocated £315m in the 2018 Budget.[156] The existing Hubs will receive £80m to continue their work, while £35m will be spent on a new national quantum computing centre and up to £70m will be awarded through the Industrial Strategy Challenge Fund.[157] In addition to this funding for the National Quantum Technologies Programme, which focuses on developing quantum technologies for application, we heard from many witnesses of the importance of maintaining or expanding funding for the fundamental science research underpinning discoveries in quantum physics.[158] Professor Sir Mark Walport, Chief Executive of UKRI, assured us that decisions over funding for fundamental research and technology development were not "either/or questions" and stated that "fundamental research needs to continue".[159] The Engineering and Physical Sciences Research Council, which is responsible for most fundamental quantum science research, currently intends to 'maintain' the level of funding for quantum technologies (rather than to 'grow' or 'reduce' it).[160] However, Professor David Delpy, Chair of the National Programme's Strategic Advisory Board, suggested that increased funding for such research would be needed from the research councils:

> A consequence of £270m going into quantum technologies is that there is increased demand on the academic side for basic quantum science development. We need to ensure that that grows. The Engineering and Physical Sciences Research Council has been very clear that it wants to continue to commit to that, but that depends on its budget.[161]

The Institute of Physics recommended that the level of funding that research councils allocate to basic quantum science research "should continue to be reviewed periodically, in consultation with the research communities", noting that "it may be that as new technological solutions and devices are developed, new avenues for basic research appear".[162]

58. In addition to the importance of supporting fundamental and applied research, the balance between larger and smaller-scale projects was also raised during our inquiry. Some, such as Dr Andrew Shields, of Toshiba Research Europe Ltd, argued that technology development projects should be larger and have longer durations in the second phase of the National Programme.[163] The UCL Quantum Science and Technology Institute added that longer timescales for commercial innovation could be incentivised through changes to the corporate tax system as well as through extending the duration of Government co-

156 HM Treasury, 'Budget 2018' (2018), para 4.20
157 HM Treasury, 'Budget 2018' (2018), para 4.20
158 For example, see: UCL Quantum Science and Technology Institute (QUT0008), paras 3 and 38; Institute of Physics (QUT0010), para 6; National Physical Laboratory (QUT0017), para 38; Dr Andrew Shields (QUT0020); QET Labs, University of Bristol (QUT0019), para 26; Qq68, 83 and 168
159 Q364
160 'Research areas: Quantum technologies theme', Engineering and Physical Sciences Research Council, accessed 9 November 2018
161 Q33
162 Institute of Physics (QUT0010), para 6
163 Dr Andrew Shields (QUT0020); see also: UCL Quantum Science and Technology Institute (QUT0008), para 20; Royal Academy of Engineering (QUT0012)

funded projects.[164] Conversely, other witnesses warned that smaller projects would still be needed, in particular given the capacity of small to medium-sized enterprises that make up a significant proportion of the current UK quantum technologies industry.[165]

59. With bids for funding from the Industrial Strategy Challenge Fund subject to competitive review, Professor Walport explained that the extent to which industry was willing to invest alongside Government funding would be one important criterion in the decision-making process.[166] This ties in with the Government Office for Science's original recommendation to continue the National Programme with "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".[167] Professor Delpy told us that the National Programme's Strategic Advisory Board anticipated that its £338m bid, if successful, would attract around £200m in matched funding from external partners.[168] However, he warned that:

> It is difficult to judge the actual commitment, because a lot of it is in kind and in the time of industrial collaborators. To be honest, it would be unfair, when we do not have an industry, to say that we need matching funding from the industry.[169]

QuantIC, the National Hub for quantum-enhanced imaging, similarly warned that "the development of new quantum technology is embryonic" and that "sustained government funding is required to maintain confidence":

> It is important that the next phase of the national programme seeks to leverage industrial funding, but in a way that takes into account the risks associated with early stage technology development and the immaturity of the supply chain. There is a real danger that premature cliff-edge withdrawal of public funding in the expectation that industry will fill the gap will result in a loss of competitiveness for the UK. Public funding should be tapered in recognition of the early stage risky nature of quantum technology.[170]

60. Professor Walport told us that he accepted Professor Delpy's concerns about expecting matched funding from a currently non-existent industry "only up to a point".[171] He clarified that matched funding would not be expected for "fundamental research" and that he would expect the National Programme to support co-investment "at that interface between academia [and industry] where it really is too early", but stated that:

> Far-sighted, technologically-based industry does invest in its research and development. Look at the pharmaceutical industry—it does an enormous amount of R&D on its own account in order to get new drugs and vaccines to market.[172]

164 UCL Quantum Science and Technology Institute (QUT0008), para 15
165 Qq167 and 205
166 Qq360 and 373
167 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p10
168 Q31
169 Q31
170 QuantIC (QUT0002), para 9
171 Q407
172 Q407

M Squared, however, described the difficulties companies faced in bringing technologies to market, and the consequent risks for private sector investment:

> The reality is that whilst significant commercial opportunities can be realised over both near-term and longer-term timescales, the sector as a whole is characterised by significant technical and market risks. On the delivery side, there are highly complex systems requiring advanced engineering developments, whilst the target markets are invariably loosely-defined or are so disruptive that the route to market remains to be mapped out.[173]

61. The National Physical Laboratory has been tasked by UK Research and Innovation with engaging with industry to explore preferred mechanisms for funding.[174] It suggested that other companies shared M Squared's concerns—telling us that it had encountered a "reluctance of large industry to invest in early stage research projects, even if there is a large, long-term potential benefit", with some companies saying they "would only invest in technologies that were a maximum of three years from market".[175] Several other witnesses not representing industry bodies, such as the Quantum Communications Hub and the Institute of Physics, also warned of the potential risks of asking more of industry than it was prepared to provide.[176]

62. Professor Sir Michael Pepper, representing the Royal Academy of Engineering, agreed that "the requirement for matched funding […] is a major disincentive" for industry when projects are expensive and have long-term returns. He told us that he thought Government funding should principally target "the buildings, depreciation and that sort of thing, to make it financially more attractive for companies to come in with a financial contribution".[177] The UCL Quantum Science and Technology Institute recommended focusing public money on "high-risk, high-gain" projects, with matched industry investment requirements for technologies that were nearer to market.[178] Professor Tim Spiller, Director of the Quantum Communications Hub, added that matched funding requirements could be made less likely to deter industry investment if the rules were made more flexible. In particular, he suggested that Innovate UK should accept "in-kind contributions" instead of cash only.[179]

63. In addition to the broad funding strategy, we heard some concerns during our inquiry regarding specific funding rules. Projects awarded Innovate UK funding must satisfy certain requirements, including:

- at least 70% of total eligible project costs should be incurred by commercial organisations; and
- a maximum of 30% of total eligible project costs are available to research participants—if there is more than one research participant, this amount will be shared between them.[180]

173 M Squared (QUT0024)
174 National Physical Laboratory (QUT0017), para 11
175 National Physical Laboratory (QUT0017), para 41
176 For example, see: University of Sussex (QUT0007), para 7.2; Quantum Communications Hub (QUT0009); Institute of Physics (QUT0010), paras 7–8; Quantum Technology Hub for Sensors and Metrology (QUT0013); Qq165–166
177 Qq94–95
178 UCL Quantum Science and Technology Institute (QUT0008), Executive Summary; see also: Q92
179 Q165
180 'General guidance for grant applicants: Participation in a project', Innovate UK, accessed 9 November 2018

Innovate UK explains in its guidance that these rules are intended to provide "funding to support and stimulate innovation in the UK economy", by "encouraging businesses to work with other commercial and research organisations".[181] However, Fraunhofer UK Research Ltd warned us that the 30% limit for non-commercial organisations prevented themselves and other research and technology organisations (RTOs[182]) from assisting some companies as fully as they could, because:

> For many of the smaller companies, undertaking 70% of a project is a daunting prospect and they may lack the expertise, [employees], and matched funds, for example, to undertake £700,000 of activity from a £1m project. Fraunhofer CAP is repeatedly asked to do more than 50% of the work and projects are being artificially trimmed in their ambition to meet the rules.[183]

64. Fraunhofer UK Research Ltd further warned that "the 30% limit prohibits meaningful consortia of multiple RTOs or combinations of Higher Education Institutions and RTOs working together on projects".[184] It advocated relaxing the rule for quantum technology projects "to enable the rapid transition of technologies from university lab, through RTO development and national lab standards to the small or medium-sized enterprise".[185] Dr Peter Thompson, CEO of the National Physical Laboratory (another RTO), agreed that flexibility in application of this rule could be beneficial:

> There could probably be a relaxation so that we identify absolutely what the right team is for the right programme and then look at the funding model. Sometimes it is the other way round; the right organisations cannot be part of the consortium because of the rules. We need some flexibility.[186]

M Squared additionally suggested that Innovate UK should review "the extent to which any one company can participate in the programme as to avoid limiting the overall investment that is made in a given funding round".[187]

65. UKRI explained that the 30% limit for non-commercial organisations was in place to "encourage greater industry commitment and investment to these projects as the endeavours become more sustainable".[188] It added:

> We continue to keep funding rules for programmes supporting the development of quantum technologies under consideration and modify these for the specific funding route if necessary. If an RTO (or any other organisation) has a compelling proposal but cannot identify a suitable

181 'General guidance for grant applicants: Participation in a project', Innovate UK, accessed 9 November 2018
182 Innovate UK defines research and technology organisations (RTOs) as non-profit entity "whose primary goal is to independently conduct fundamental research, industrial research or experimental development or to widely disseminate the results of such activities by way of teaching, publication or knowledge transfer"—' General guidance for grant applicants: Research organisations', Innovate UK, accessed 9 November 2018
183 Fraunhofer UK Research Ltd (QUT0021)
184 Fraunhofer UK Research Ltd (QUT0021)
185 Fraunhofer UK Research Ltd (QUT0021)
186 Q306
187 M Squared (QUT0024)
188 UK Research and Innovation (QUT0031)

> competition to seek funding, we would encourage them to talk to us, through one of our councils, so we could explore an appropriate funding route.[189]

66. **It is right that the Government should look to industry to contribute to funding for technology development, especially as quantum technologies grow closer to commercialisation. However, it is important that matched funding requirements do not prevent important work from going ahead. Other funding rules, such as the 30% limit on project funding awarded to non-commercial organisations, can also restrict the scope of some projects.**

67. ***Innovate UK should ensure that there is flexibility in rules where State Aid rules and other relevant regulations allow it, and design the rules applying to funding calls around the aims of the project rather than designing projects around the standard rules. In particular, the 30% limit on funding that can be awarded to non-commercial organisations should be relaxed where it hampers applications for funding calls or the scope of the projects funded. UK Research and Innovation should monitor the impact of any matched funding requirements and ensure that such conditions do not detriment the development of quantum technologies in the UK. It should take into account 'in-kind' contributions (such as time, access to facilities or training) from industry rather than pure investment alone, and continually review the funding environment in the UK compared to other quantum technology programmes internationally, to ensure that the UK remains competitive. The Government should prioritise spending on initiatives or capital that will benefit the development of the wider UK quantum technologies industry alongside those projects that will encourage co-investment from industry.***

68. ***UK Research and Innovation, in co-operation with the new Executive Board, should regularly review the funding available to fundamental research in quantum science. As the Government aims to increase spending on research and development to 2.4% of GDP, and as the National Quantum Technologies Programme develops the application and commercialisation of quantum technologies, the Government should be ready to provide the funding required to ensure fundamental research keeps pace. UK Research and Innovation should additionally ensure that projects of a variety of scale and duration are funded, to ensure that opportunities exist for organisations of all sizes.***

Demonstrator projects and Government procurement

69. The Quantum Engineering Technology (QET) Labs, at the University of Bristol, told us that "the UK's quantum industry is in its early stages and mainly consists of a small number of start-ups",[190] which tend to produce components for quantum-enabled products rather than the final products themselves.[191] Professor Delpy explained that the next stage of a quantum industry would involve "systems integrators" (larger companies producing final products, such as an automotive manufacturer building new cars) incorporating quantum components into their products.[192] Dr Graeme Malcolm, CEO of M Squared, similarly explained that a fully-developed industry would "need to have

189 UK Research and Innovation (QUT0031)
190 QET Labs, University of Bristol (QUT0019)
191 See also: QuantIC, University of Glasgow (QUT0002), para 12; Q15
192 Qq5, 15 and 22–23

the basic components, the supply chains, the integrations and the end users all lining up together”.[193] The Quantum Communications Hub, however, warned that demand from end-users was currently low:

> Perhaps the biggest barrier remaining for the commercialisation and uptake of quantum communications technologies is the growth of markets and the stimulation of market pull. Disruptive technologies often start with ‘technology push’ and this now needs to change.[194]

The Ministry of Defence agreed that “the first priority [for the second phase of the National Programme] should be engaging industry and end-users to stimulate technology translation and early adoption”.[195]

70. Fraunhofer UK Research Ltd told us that it perceived “a realisation in industry that quantum technology is coming” and said that “there is now a glint in the eye of Tier 1 companies at the very mention of quantum technologies”.[196] This was not, however, a common opinion.[197] Professor Knight warned:

> There is low industry awareness, and it worries me. When I am in North America and talk to CEOs and chairs of companies, they are fully aware of new technologies and their development. There is not quite that sense yet in some of the big companies here in the UK, so we need to do more work on it.[198]

Dr Peter Thompson, CEO of the National Physical Laboratory, told us that although large parts of industry did not yet recognise the potential of quantum technology, his experience of engaging with large companies indicated that attitudes could be changed “quite rapidly”.[199] The National Physical Laboratory recommended that “in order to better engage large industry, near-market technology solutions need to be practically demonstrated, to provide industry with the confidence to invest in this area”.[200] Support for such demonstrator projects was widespread among our witnesses.[201] Dr Thompson emphasised that “proof of value, or the route to proof of value” must be demonstrated, “rather than proof of concept”.[202]

71. The Government Office for Science noted in its 2016 report on quantum technologies that the “Government is not subject to the same near-term commercial constraints as private sector organisations”, which “gives it a unique ability to act as a demonstration client”.[203] The Institute of Physics told us, however, that—outside the defence sector—

193 Q188
194 Quantum Communications Hub (QUT0009)
195 Ministry of Defence (QUT0026), para 22
196 Fraunhofer UK Research Ltd (QUT0021)
197 For example, see: University of Strathclyde (QUT0004); Institute of Physics (QUT0010), para 11; PA Consulting Group (QUT0014), para 3; Qq302 and 368
198 Q40
199 Q302
200 National Physical Laboratory (QUT0017), para 41
201 For example, see: Quantum Technology Hub for Sensors and Metrology (QUT0013); Institute of Physics (QUT0010), para 9; PA Consulting Group (QUT0014), para 14; National Physical Laboratory (QUT0017), paras 41 and 48; EU COST action QTSpace (QUT0018); Qq142, 231, 279 and 297
202 Q303
203 Government Office for Science, ‘The Quantum Age: technological opportunities’ (2016), p48

public bodies could be supporting more demonstrator projects.[204] Professor Kai Bongs, Director of the National Quantum Hub for Sensors and Metrology, told us that his Hub had been involved in two demonstrator projects funded by the Defence Science and Technology Laboratory, and that these had "proven extremely efficient in deeply involving the industry".[205] He outlined the sort of demonstrator projects that he felt the Government should be looking to support:

> We see benefits mainly in areas where there is large public interest but maybe more fragmented and smaller scale company infrastructure projects. For instance, the Department for Transport could look into sensors for drainage under rail tracks or sinkholes under roads, which are billion-level problems, but are quite hard to solve with conventional technologies; or you might think about [the Department for Environment, Food and Rural Affairs] investing in sensors to look for river embankments in flood areas.[206]

Indeed, we heard of a variety of potential demonstrator projects during the course of our inquiry, such as:

- atomic clocks and quantum sensors could be used to develop systems that deliver short-term precision-timing and navigational capability, providing resilience to temporary interruptions in global navigation satellite systems;[207]
- quantum sensors could provide accurate mapping of structures and conditions underground, which could help construction projects plan around hidden obstacles to avoid delays and additional costs;[208]
- quantum cryptography systems could be integrated into communication networks to enhance communication security;[209]
- space-based ventures could stimulate the development of quantum technologies for more conventional use, for example satellite-mounted quantum sensors could improve natural resource discovery and environmental monitoring;[210] and
- in the longer term, quantum computers may find diverse applications, including for drug development, product design or logistical management.[211]

72. The Science Minister, Sam Gyimah MP, assured us that he was "looking at the opportunity for Government to play a role in [the development of quantum technologies] as a procurer of innovation".[212] However, pressed on what he was doing to encourage Government support for technology demonstration projects outside of the Ministry of Defence, the Minister told us that:

204 Institute of Physics (QUT0010), para 9
205 Q231
206 Q231
207 For example: Teledyne e2v (QUT0016); National Physical Laboratory (QUT0017), para 54; Qq297–299; National Physical Laboratory (QUT0028); see also: Government Office for Science, 'Satellite-derived Time and Position: A Study of Critical Dependencies' (2018), p69
208 Institute of Physics (QUT0010), para 9 and Q300
209 Q300
210 EU COST action QTSpace (QUT0018); Q300
211 Airbus (QUT0001); Manchester Metropolitan University (QUT0003), para 13; Qq82 and 300
212 Q380

> My Department […] does a lot of work with [the Department for Digital, Culture, Media and Sport]. We are currently going through a review of quantum computing and quantum technologies. We will report by the end of this year, and there will be recommendations for Ministers to follow […] As for other Departments, there is work going on, but it is not directly within my area of responsibility to drive the quantum technologies and how they could be exploited in the transport Department.[213]

Professor Sir Mark Walport, Chief Executive of UKRI, added that "the chief scientist network has an important role to play" in raising awareness of the potential of quantum technologies across Government.[214]

73. **Awareness across industry of the potential for quantum technologies, in particular in the short-term, needs to be improved.** ***The new Executive Board should engage with businesses and industry bodies that are not yet actively pursuing opportunities presented by quantum technologies, articulating the near-term capabilities expected of such technologies and investigating what specific product requirements and technology demonstrations are needed to drive uptake in different sectors. This activity should aim to raise industrial awareness of quantum technologies and feed into the Executive Board's roadmap and strategy for developing the UK quantum technologies industry.***

74. **We commend the Ministry of Defence on its support for quantum technology demonstrator projects. Similar opportunities exist for other Government departments to support the development of quantum technology products that they would benefit from, with the added advantage of assisting the nascent UK quantum industry by demonstrating the value of quantum technologies to other potential end-users.** ***In collaboration with the Chief Scientific Adviser network, the new Executive Board of the National Quantum Technologies Programme should identify opportunities for Government Departments to support quantum technology demonstrator projects and encourage their uptake by assessing the positive impacts that such projects could achieve for the Department and for the UK quantum technologies industry, if successful.***

The Small Business Research Initiative

75. The opportunity for Government departments to support the commercialisation of new technologies is the focus of the Small Business Research Initiative (SBRI),[215] which aims to "help [innovators] demonstrate and develop their new technologies" as well as "[helping] government organisations solve tough challenges by connecting them with innovative businesses".[216] The SBRI provides support to public bodies, through Innovate UK, to run competitions inviting businesses to bid for contracts to develop innovative solutions to specific challenges faced by the public sector body.[217] The initiative was re-launched in 2008 but was not allocated any defined funding.[218] An independent, Government-commissioned review of SBRI (the 'Connell Review') concluded in 2017 that

213 Q377
214 Q401
215 'SBRI: the Small Business Research Initiative', UK Research and Innovation, accessed 6 November 2018
216 Innovate UK, 'SBRI' (2017)
217 Innovate UK, 'Government Challenges, Ideas from Business, Innovative Solutions' (2015)
218 David Connell, 'Leveraging Public Procurement to Grow the Innovation Economy: An Independent Review of the Small Business Research Initiative' (2017), p38

"the public sector is still not taking full advantage of SBRI's potential".[219] It noted that SBRI spending targets were missed before being abandoned, and that spending fell by 24% from 2014–15 to 2015–16, the last year for which records are available.[220] The review made several recommendations on how to make better use of the opportunity presented by SBRI, including:

- the establishment of a central SBRI fund into which public sector organisations could bid to fund a programme of SBRI competitions, to reach around £250m per annum within six years;
- the establishment of a 'National SBRI Fund Board', comprising public and private sector representatives, to oversee the central SBRI fund, set funding conditions and guidelines for SBRI programmes and review departmental or agency programme proposals; and
- the introduction of a third phase of funding for a small number of projects, combined with a drive to ensure that funding for first and second phase projects meet guidelines (£50,000–100,000 for Phase 1 and £250,000–1m for Phase 2).[221]

76. We wrote to the Chancellor of the Exchequer in April 2018, seeking clarification on how the Government intended to act upon the recommendations of the Connell Review.[222] In response, the Secretary of State for Business, Energy and Industrial Strategy informed us that the Government was "taking on board recommendations for a central fund and the need for departments to build SBRI capability", but set out no new measures that it would take beyond what had been set out in the Industrial Strategy White Paper.[223] The White Paper, however, was published prior to the publication of the Connell review and so did not respond to its recommendations.[224] Instead, it announced the Government's intention to "refocus the SBRI to increase its impact for innovative businesses", aligning it with the Government's Grand Challenges, and to establish a GovTech Catalyst as "a first step" towards "building capability in the public sector to drive productivity by adopting SBRI solutions".[225] The GovTech Catalyst was created to "help public bodies to identify challenges that could be solved with new digital technologies and build capability to run SBRI competitions".[226] It has been allocated £20m to support 15 challenges over three years.[227]

219 David Connell, 'Leveraging Public Procurement to Grow the Innovation Economy: An Independent Review of the Small Business Research Initiative' (2017), p7; The Government acknowledged to our predecessor Committee that SBRI had "yet to reach its full potential"—House of Commons Science and Technology Committee, Second Special Report of Session 2017–19, 'Managing intellectual property and technology transfer: Government Response', HC 318, p3

220 David Connell, 'Leveraging Public Procurement to Grow the Innovation Economy: An Independent Review of the Small Business Research Initiative' (2017), pp38–42

221 David Connell, 'Leveraging Public Procurement to Grow the Innovation Economy: An Independent Review of the Small Business Research Initiative' (2017), pp14–17

222 Letter from Rt Hon Norman Lamb MP, Rt Hon Nicky Morgan MP and Rachel Reeves MP to Rt Hon Philip Hammond MP, 24 April 2018

223 Letter from Rt Hon Greg Clark MP to Rt Hon Norman Lamb MP, Rt Hon Nicky Morgan MP and Rachel Reeves MP, 15 May 2018

224 HM Government, 'Industrial Strategy: Building a Britain fit for the future'

225 HM Government, 'Industrial Strategy: Building a Britain fit for the future', p70; The Grand Challenges are intended to improve UK lives and productivity by addressing major global changes, currently comprising 'artificial intelligence and data', 'ageing society', 'clean growth' and 'future of mobility'—HM Government, 'Industrial Strategy: Building a Britain fit for the future', pp30–55

226 Letter from Rt Hon Greg Clark MP to Rt Hon Norman Lamb MP, Rt Hon Nicky Morgan MP and Rachel Reeves MP, 15 May 2018

227 'GovTech Catalyst information', Government Digital Service, accessed 6 November 2018

77. Despite the lack of any clear proposed action to promote the use of SBRI to support the development of a UK quantum technologies industry, the Science Minister told us that the Government was "looking at how [it] could use [the SBRI] more actively".[228]

78. **We agree with the Connell Review that the Small Business Research Initiative has a "unique and valuable role to play in the innovation and procurement landscape", supporting UK businesses in developing innovative new products while enabling public sector bodies to source innovative solutions to the challenges they face. However, the Government's response to the Connell Review so far appears limited. The GovTech Catalyst only supports public bodies in sourcing digital technology solutions and the three-year, £20m GovTech Fund is significantly smaller than the £250m that the Connell Review recommended to be spent per annum through SBRI, or the £200m target the Government had for SBRI spending in 2014–15.** ***We recommend that the Government fully adopts the recommendations of the Connell Review, and establishes a central SBRI fund with a National Board to oversee its delivery as part of the 2019 Spending Review.***

79. **Quantum technologies promise significant opportunities for UK economic growth as well as improvements to Government departments' capabilities. Quantum technologies are therefore particularly well-suited to the aims and implementation of the Small Business Research Initiative.** ***We recommend that the Government establishes a QuantumTech Catalyst to drive public sector organisations' use of the Small Business Research Initiative for quantum technologies, in the same way that the GovTech Catalyst has for digital technologies. The new QuantumTech Catalyst should seek to launch a first round of challenges within six months of this Report's publication.***

228 Q380

6 Continuing the National Programme—Skills

80. A current or imminent skills shortage was identified as an obstacle to the growth of quantum technology activity in the UK by a wide variety of witnesses.[229] For example, Airbus told us that "the UK simply will not have enough engineers trained to meet the future demand for quantum-based solutions".[230] The University of Sussex told us that "there is a severe skills shortage of qualified quantum engineers", and that in their opinion, this shortage was "the most crucial challenge" facing the UK quantum sector.[231] Professor John Morton, Director of the Quantum Science and Technology Institute at University College London, qualified that "the lack of skilled people in quantum technologies is currently a key bottleneck not just in the UK but around the world".[232]

81. The National Quantum Technologies Programme currently supports PhD-level training through three Centres for Doctoral Training focusing on quantum engineering and three Training and Skills Hubs in Quantum Systems Engineering, as well as through the Doctoral Training Partnership funds for PhD studentships at the Quantum Technology Hubs.[233] This has been complemented with PhD funding from the Defence Science and Technology Laboratory, which has so far supported 46 studentships.[234] The National Programme has additionally invested £16m in a quantum technology fellowship programme, to fund 14 "key researchers" to develop their careers.[235] Professor Morton told us that "the UK can be said to be world leading in training and skills in quantum technologies", citing industry approval and interest from international competitors who want to learn more about the UK's training programmes.[236] Indeed, many witnesses emphasised the importance of continuing the different elements of the National Programme's current training schemes into the second phase.[237] Professor Martin Dawson, Head of the Fraunhofer Centre for Applied Photonics, agreed that "UK universities are very good at training highly qualified people" in quantum science, and that the Centres for Doctoral Training were "aligning themselves to training […] quantum engineers" rather than physicists, which he viewed as "a really crucial thing".[238] However, along with several other witnesses, he warned that the existing training programmes were not training enough students.[239]

229 See, for example: Airbus (QUT0001); Networked Quantum Information Technologies Hub (QUT0006), para 11.1; University of Sussex (QUT0007), para 4.2; UCL Quantum Science and Technology Institute (QUT0008), para 16; Institute of Physics (QUT0010), para 17; Quantum Technology Hub for Sensors and Metrology (QUT0013), section 7; Professor Sir Peter Knight (QUT0015); National Physical Laboratory (QUT0017), para 52

230 Airbus (QUT0001)

231 University of Sussex (QUT0007), paras 4.2 and 5.1

232 Q113

233 National Quantum Technologies Programme, 'Growing a skilled workforce in quantum technologies' (2016); UK Research and Innovation (QUT0031)

234 National Quantum Technologies Programme, 'Growing a skilled workforce in quantum technologies' (2016)

235 National Quantum Technologies Programme, 'Growing a skilled workforce in quantum technologies' (2016)

236 Q113

237 See, for example: University of Sussex (QUT0007), paras 4.5–4.6; Professor Sir Peter Knight (QUT0015); QET Labs, University of Bristol (QUT0019), para 10; Qq113, 240 and 262

238 Q214

239 Q214; see also: University of Sussex (QUT0007), paras 4.2–4.4; National Physical Laboratory (QUT0017), para 52

82. Besides the shortage of suitably-qualified personnel, Dr Malcolm, CEO of M Squared, told us that the UK also had a "global disadvantage" in the "mix between commercial and technical skills" available in its workforce:

> More education in the management of technological innovation and the commercialisation of it would help a lot. That is the really rare bit—we struggle to find people that can close $20 million business, because we need that detailed mix of skills there.[240]

This tallies with the conclusions of a 2018 report on science, technology, engineering and mathematical (STEM) training in the UK, published by the National Audit Office.[241] This did not focus specifically on quantum technologies, but similarly reported that the UK's STEM skills problem consisted more of a skills "mismatch" than a simple shortage, with STEM graduates frequently lacking the employability and practical skills needed to enter the workforce.[242]

83. The National Quantum Technologies Programme established three Training and Skills Hubs in Quantum Systems Engineering in recognition of the fact that "quantum engineers are multi-disciplinary individuals who combine practical engineering skills and specialist technical knowledge […] with broader communication skills, commercial awareness and engineering skills".[243] The Training and Skills Hubs were based at universities and were intended to train quantum engineers through taught courses, research project-based doctoral training and networking activities. They also offer co-working and mobility initiatives, such as secondments, intensive short courses, workshops and mentoring schemes, to integrate training with quantum technologies communities in academia, industry, government and civil society. However, the three Hubs combined train only around 20 students per year.[244]

84. Professor Kai Bongs, Director of the National Hub for Sensors and Metrology, indicated that engaging industry in the design and delivery of training programmes could be beneficial for students and businesses alike:

> We have good experiences with secondment programmes between us and Teledyne e2v and between us and M Squared, for instance. Companies have a large appetite to take secondments of students for half a year, which helps make the students aware of the company, and it provides a little prod and the possibility for existing engineers in the company to get informed.[245]

85. In addition to providing students with the softer skills and work experience that they might not otherwise gain, and helping to raise awareness of quantum science at the host company, we heard that industry involvement in training programmes could also ease funding constraints. QuantIC, the national Hub for quantum-enhanced imaging, told

240 Q214; Teledyne e2v similarly told us that "the quantum programme needs to become alert" to the fact that the skills it needs to engage "are not wholly academic skills"—Teledyne e2v (QUT0016)

241 National Audit Office, 'Delivering STEM Skills for the Economy' (2018)

242 National Audit Office, 'Delivering STEM Skills for the Economy' (2018), paras 10 and 2.13–2.21

243 Engineering and Physical Sciences Research Council, 'Training and Skills Hubs in Quantum Systems Engineering: Invitation for proposals' (2015)

244 This figure is based on past student numbers and future spaces available at the three Hubs: Imperial College London, 'Quantum Systems Engineering Skills and Training Hub: Frequently Asked Questions'; University of Bristol Quantum Technology Enterprise Centre, 'QTEC Fellows 2017–18'; and UCL Quantum Science and Technology Institute, 'CDT and Skills Hub'—all accessed 7 November 2018

245 Q262

us that by introducing industrially-led PhD studentships, they had leveraged £481,000 of industrial funding to match £500,000 of their own investment and fund 12 studentships.[246] However, QET Labs, at the University of Bristol, warned us that the Government could not yet expect industry to fully fund training as "businesses do not yet project significant enough return on investment to support PhDs conducting this fundamental research".[247]

86. Professor Bongs suggested that there was a strong appetite from industry to support quantum technology training schemes, with universities currently "oversubscribed" with companies wanting to host secondments.[248] Dr Andrew Shields, Quantum Technologies R&D Lead for Toshiba Research Europe Ltd, told us that Toshiba supported "a lot of PhD studentships" through the Centres for Doctoral Training and through secondments, which he said had worked well.[249] However, we heard from other companies working in the field that they supported relatively few studentships.[250] Dr Mark Bentall, Head of Technology Development and Innovation at Airbus Defence and Space, explained that studentship opportunities at Airbus were constrained by the limited amount of work it was undertaking on quantum technologies, and indicated that more opportunities could be created if the National Programme instigated challenge-based technology development projects.[251] Professor Trevor Cross, Chief Technology Officer at Teledyne e2v, advised that more flexible mechanisms for industry engagement could facilitate increased industry support for training programmes:

> The Centres for Doctoral Training work best if you get in at the beginning, which means once every five years when the CDTs are refreshed […] That once-every-five-years opportunity is probably not the best for engaging industry, which may not be able to do it one year; but next year, when the boat has left the port, it might be possible.[252]

Another factor that may have contributed to the low number of students supported by some companies was the perceived lack of influence over the content and delivery of training programmes that some companies reported.[253]

87. The Government announced that the £235m allocated for the extension of the National Quantum Technologies Programme would cover:

> A new training and skills package, including Centres for Doctoral Training, that will inspire people to consider careers uncovering the opportunities that will come with quantum technologies.[254]

246 QuantIC (QUT0002), para 2
247 QET Labs, University of Bristol (QUT0019), para 12
248 Q263
249 Q333
250 Qq335–336
251 Qq336 and 339–340; see also Airbus (QUT0001)
252 Q335
253 For example, see: Qq214 and 330
254 'New funding puts UK at the forefront of cutting edge quantum technologies', Department for Business, Energy and Industrial Strategy and Department for Digital, Media, Culture and Sport, accessed 6 November 2018

UKRI additionally informed us that quantum technologies were "a priority in the Engineering and Physical Sciences Research Council's 2018 call for Centres for Doctoral Training".[255] Decisions on funding for the continuation of existing Centres for Doctoral Training and the establishment of new ones are due to be taken toward the end of 2018, in time for new student cohorts to start in October 2019.[256]

88. **There is significant concern in the quantum technology community that the future development of quantum technologies in the UK could be constrained by the lack of a suitably skilled workforce. This skills shortage is not unique to the UK, and the existing training programmes provided under the National Quantum Technologies Programme are well-regarded, but increasing and improving the training offered must be a priority for the second phase of the National Programme.**

89. ***The Government should continue and expand the National Quantum Technologies Programme's current training programmes. The new Executive Board, in co-operation with UKRI, should engage with companies working on quantum technologies or closely related fields to help tailor the content of doctoral training programmes to ensure that they provide the balance of skills needed by industry. This will require exposure to commercial practices and requirements, which could be provided through secondments, industry-led projects during the first year of a Centre for Doctoral Training course or industry-proposed and sponsored PhD projects. This should be completed in time for renewal of the Centres for Doctoral Training next year. Furthermore, UKRI should find ways to make the terms on which industry can input into training programmes more flexible, to facilitate increased engagement (for example by enabling input outside of the five-year funding cycles of Centres for Doctoral Training). In exchange, UKRI should seek contributions from industry to fund additional studentships. The Government should be ready to co-invest where industry funding is available.***

Qualification levels

90. Professor Morton told us that quantum technology "is an area that requires some very advanced training", and that "the skills required to make a big impact in this area are at the masters or postgraduate level at present".[257] However, many other witnesses felt those with lower qualification levels were already needed or would be needed soon.[258] Jonathan Flint, President-Elect of the Institute of Physics, argued that:

> As near-to-market products are produced, we will need apprentice-level skills in things like electronics and cryogenics—people who do hands-on manufacture and testing of those very complex things.[259]

Professor Ian Walmsley, Director of the Networked Quantum Information Technologies Hub, warned that the Hubs were already "beginning to see […] difficulty in getting the skilled engineers who are needed to take the technology out of the laboratory and build

255 UK Research and Innovation (QUT0031)
256 'CDT and Skills Hub', UCL Quantum Science and Technology Institute, accessed 9 November 2018
257 Qq113 and 115
258 For example, see: Qq115–116, 216 and 265
259 Q115

the next stage", adding that "it is likely that high-level technical and technician skills will also be needed".[260] He noted that training at these levels was "not properly catered for in the current programme".[261] The Institute of Physics similarly warned us that:

> Training support is needed on a larger scale and at differing entry points [than currently provided by the National Quantum Technologies Programme]—for example, at apprenticeship level. Any new quantum technologies programme must include a strategy for skills development that addresses the future needs of the entire quantum technologies supply chain, and should not be limited to Centres for Doctoral Training.[262]

Professor Walmsley suggested that "there are opportunities to [deliver technical training], by partnering with the skills agency, further education colleges and [other new partners]".[263]

Technical education and continuing professional development

91. The Government announced reforms to technical education in 2016, with existing apprenticeship 'frameworks' being replaced by new, employer-designed 'standards' and the introduction of 'T Levels', which will provide college-based technical education equivalent to A Levels.[264] T Levels will encompass training in technical and practical skills as well as extended periods of work experience with relevant employers.[265] The Government has created a framework of 15 'occupational routes'—groups of occupations that share common knowledge, skills and behaviours—to which every T level and apprenticeship standard will belong. There will be one T level for each of 11 of these routes, including 'health and science' and 'engineering and manufacturing'.[266] The 'occupational maps', detailing the skilled occupations that can be achieved through an apprenticeship or T Level in each route, have been published and contain roles relevant to quantum technologies, such as science technicians and design and development technicians.[267] However, many of the corresponding apprenticeship standards are still in development, as is the content of the new T level curricula.[268] Apprenticeship standards are developed by 'trailblazer' groups of ten or more employers overseen by the Institute for Apprenticeships, while T level curricula are being developed by T level panels made up of employers, professional bodies and educational providers, convened by the Department for Education.[269] The Department for Education has said that it "will begin engaging much more comprehensively with employers" once the pilot phase for T levels ends in 2019, to

260 Q261
261 Q261
262 Institute of Physics (QUT0010), para 18; Professor Kai Bongs, Director of the Quantum Technology Hub for Sensors and Metrology, similarly told us that "we should look not only at engineers, but at highly skilled technicians. There is more need to provide new training in that area"—Q265
263 Qq261–262
264 Department for Business, Innovation and Skills and Department for Education, 'Post-16 Skills Plan' (2016)
265 Department for Education, 'Implementation of T Level Programmes: Government consultation response' (2018)
266 Department for Education, 'Post-16 Technical Education Reforms: T Level action plan' (2017), pp10–14; Department for Education, 'Implementation of T Level Programmes: Government consultation response' (2018), p18
267 'Occupational Maps', Institute for Apprenticeships, accessed 7 November 2018; Institute for Apprenticeships, 'Occupational Map: Engineering and Manufacturing' and 'Occupational Map: Health and Science' (2018)
268 Institute for Apprenticeships, 'Occupational Map: Engineering and Manufacturing' and 'Occupational Map: Health and Science' (2018); Department for Education, 'Post-16 Technical Education Reforms: T Level action plan' (2017), p13
269 Institute for Apprenticeships, ''How to' guide for trailblazers' (2017), p ; Department for Education, 'Post-16 Technical Education Reforms: T Level action plan' (2017), pp12–14

"design the detail of qualifications, deliver work placements and ensure the broader system is ready for T level delivery".[270] However, the National Audit Office has found that "many employers, particularly small and medium-sized enterprises, struggle to engage with the design process [for apprenticeships] due to the resources required".[271] It also noted that:

> Some further education providers have reported difficulties accessing capital funding under the new funding system led by Local Enterprise Partnerships, and are therefore disincentivised from taking on the financial risk involved in running costly STEM courses.[272]

92. Training in quantum technologies will be needed for existing members of the UK workforce, as well as those joining it. Dr Mark Bentall, Head of Technology Development and Innovation at Airbus Defence and Space, explained that Airbus had an engineering workforce of 8,500, "very few of whom understand quantum technologies and how they can exploit and use them". He argued that this was "the workforce we need to bring up to speed".[273] Professor Trevor Cross, Chief Technology Officer at Teledyne e2v, also raised the need for existing engineers to be trained in quantum technologies:

> I am thinking about more continuing professional development and short courses. I would like my already degree-qualified people to be able to dip into shorter courses in universities. I know that those things exist, but today the mechanisms are a bit clunky and difficult when we are trying to get people from industry in to get a bit of exposure. I would like to see more in that area.[274]

Dr Peter Thompson, Chief Executive Officer of the National Physical Laboratory, proposed focused training courses for existing employees as an efficient way of improving awareness of quantum technologies:

> We heard many times from industry that we should come to companies and train 100 staff in what quantum technology means for them. That is a very efficient way to do it. If the programme can support that kind of modular training course to get out into companies, it will make a difference very early.[275]

The UCL Quantum Science and Technology Institute agreed that a priority for the next phase of the National Programme should be to "[augment] the population of informed decision-makers in finance and business". It noted that the identification of applications for quantum devices had so far been "strongly dependent on companies who happen to have informed 'quantum champions' among their workforce", leading it to recommend that "the UK's training offerings should prioritise the enlargement of this cohort".[276]

270 Department for Education, 'Post-16 Technical Education Reforms: T Level action plan' (2017), pp17–18
271 National Audit Office, 'Delivering STEM Skills for the Economy' (2018), para 3.9
272 National Audit Office, 'Delivering STEM Skills for the Economy' (2018), para 3.10
273 Q337
274 Q327
275 Q328
276 UCL Quantum Science and Technology Institute (QUT0008), Executive Summary and para 5

93. It is not clear what the new "training and skills package" announced for the next phase of the National Quantum Technologies programme will cover beyond Centres for Doctoral Training.[277] UKRI told us that it was "seeking to increase skills at all levels, to maintain a broad disciplinary talent base, and work with partners to identify key skills gaps and build capacity across disciplines", and had therefore "committed to develop a longer-term talent strategy, working closely with [its] partners".[278]

94. **The future workforce required for a successful UK quantum technologies industry will not be composed entirely of PhD-level graduates and above. Although workers at lower qualification levels may not need skills as specifically tailored to quantum technologies as for those with higher qualifications, the growth of a quantum technologies industry will add to the demand for engineering and scientific graduates, technicians and apprentices. In addition to training being required for those entering the workforce, we believe that it is also required for engineers, technicians and others already in the workforce.**

95. ***The second phase of the National Quantum Technologies Programme must ensure that appropriate training is available at undergraduate, technician and apprenticeship level, alongside continued provision at PhD level. It should provide training opportunities for established workers as well as for those entering the workforce, for example through continuing professional development modules or short university-based courses, in a manner that is easy for companies to access. There should also be periodic, sector-specific workshops available to end-users of quantum technologies, with the aim of growing a network of quantum 'champions' in sectors where quantum technologies can already start to be applied. These modules, courses and workshops should all be available within three years of the publication of this Report.***

96. ***The new Executive Board should engage with companies to ensure, facilitate and co-ordinate input from quantum technologies enterprises—both large companies and small and medium-sized enterprises—into the Institute for Apprenticeships' ongoing work on the development of apprenticeship standards and the 'health and science' and 'engineering and manufacturing' T levels. This endeavour should ensure that these training routes: flag the opportunity of the quantum technologies sector to students; cover the basic skills that enterprises working with quantum and related technologies require; and offer apprenticeships or work placements with enterprises working in the quantum sector. The Executive Board should encourage and support quantum technology enterprises to offer apprenticeship places and work placements.***

277 'New funding puts UK at the forefront of cutting edge quantum technologies', Department for Business, Energy and Industrial Strategy and Department for Digital, Media, Culture and Sport, accessed 6 November 2018
278 UK Research and Innovation (QUT0031)

7 The societal implications of quantum technologies

97. As with most new technologies, quantum technologies present a variety of potential benefits and risks to society. This Chapter explores what these are, and considers ways in which they can be managed.

Potential societal impacts

98. The applications described in paragraphs 9 to 15 of this Report illustrate the potential for quantum technologies to benefit society across fields as diverse as medicine, construction, transport or telecommunication. Indeed, Professor Sir Mark Walport, Chief Executive of UK Research and Innovation, told us that there is "hardly any sector that does not have the opportunity to benefit" from quantum technologies.[279] This variety of potential uses, as well as the success of the first generation of quantum technologies, provides some of the optimism for the potential of the next generation. In 2016, the Government Office for Science estimated that altogether, quantum technologies could grow to be comparable to the consumer electronics manufacturing sector, then worth £240bn per year worldwide.[280] Although the Quantum Technology Hub for Sensors and Metrology cautioned that the "diversity and the underpinning nature of [quantum] technology makes predictive quantification of market size challenging",[281] we heard widespread agreement that the market potential for quantum technologies was substantial, whatever precise value it might finally cover.[282]

99. Professor Hensinger added that, beyond widespread technological applications, an additional societal benefit from research into quantum technologies is its unique ability to inspire young people to take an interest in science, technology, engineering or mathematics subjects:

> When I was young, there was a space programme. It was on the back of breakfast cereal packages, and, to be honest, the reason I am here is that I wanted to be the science officer on the Enterprise. With quantum computing, I now see a very similar thing.[283]

100. As with any new technology, there are, however, potential risks as well as opportunities. For example, the Royal Academy of Engineering told us that quantum technology could increase the speed and capacity of data analysis, and that "by accelerating the scope of artificial intelligence there will be positive and negative societal implications across the areas of health, security, privacy and equality".[284] The Networked Quantum Information Technologies Hub noted that quantum sensors, such as small, accurate navigational devices, could "open up opportunities for innovative personalised services, but at the

279 Q366
280 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p56
281 Quantum Technology Hub for Sensors and Metrology (QUT0013); Jonathan Flint, President-Elect of the Institute of Physics, agreed that "the products, competitors and industrial landscape are not yet defined, so no one can rightly say this will be worth £100 billion or whatever in X years"—Q77
282 For example, see: Dr Andrew Shields (QUT0020), M Squared (QUT0024) and Qq78, 223–224 and 275
283 Q237
284 Royal Academy of Engineering (QUT0012)

same time create new risks related to monitoring, profiling and social control".[285] Several witnesses, including UKRI, told us that the societal implications of quantum technologies would develop similarly to other technological advances and could mostly be managed through existing regulatory frameworks.[286] However, Professor Knight told us that quantum technology was "a revolutionary cross-sectoral technology, the deployment of which will have an impact on society as great as the digital revolution".[287] The Networked Quantum Information Technologies Hub made the point that "it is still very early to assess the most likely applications for quantum information technologies".[288] It noted, however, that if certain quantum technologies did provide dramatic improvements in capability but at high initial cost, then this could led to potentially problematic concentrations of power among the few organisations with access to such technologies.[289]

101. One particular issue was the anticipated ability of quantum computers to undermine conventional digital security methods.[290] Currently, when sensitive digital information is communicated between two points, it is usually protected by being transmitted in an 'encrypted' form.[291] A mathematical 'encryption key' is used to convert the information into a format that can only be meaningfully interpreted by being converted back to its original form using a corresponding 'decryption key'. The calculations that are required to be able to break such encryption methods would take conventional computers millions of years to complete but could rapidly be performed by a quantum computer.[292] The Government Office for Science has warned that the development of a quantum computer large enough to be able to easily crack cryptographic defences in this way would have "such serious consequences that it is sometimes called the crypto-apocalypse".[293] Professor Knight warned that this problem needed to be taken seriously:

> We have to assume that the encryption we use to secure the Internet will fail within the decade […] All the things we do when we use [standard Internet security methods] for secure engagement—trading, commerce, entertainment and securing our own identity—have to be rolled up in a replacement within a decade.[294]

However, he indicated that the Government, industry and academia had started work on replacement systems that would be safe from quantum computers, which he was confident would avert the potential security risk "provided […] that we do not lose our nerve on the

285 Networked Quantum Information Technologies Hub, 'Thinking Ahead to a World with Quantum Computers: The Landscape of Responsible Research and Innovation in Quantum Computing' (2016), p47
286 For example, see: Quantum Communications Hub (QUT0009); Quantum Technology Hub for Sensors and Metrology (QUT0013); UK Research and Innovation (QUT0023), para 27; Ministry of Defence (QUT0026), para 29; Q128
287 Professor Sir Peter Knight (QUT0015)
288 Networked Quantum Information Technologies Hub (QUT0006), para 12.1
289 Networked Quantum Information Technologies Hub, 'Thinking Ahead to a World with Quantum Computers: The Landscape of Responsible Research and Innovation in Quantum Computing' (2016), pp40 and 60–61
290 For example, see National Institute of Standards and Technology, 'Report on Post-Quantum Cryptography' (2016)
291 For more information, see: 'Data Encryption', POSTbrief 19, Parliamentary Office of Science and Technology, March 2016
292 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p16
293 Government Office for Science, 'The Quantum Age: technological opportunities' (2016), p50
294 Q7

funding of the National Programme".[295] Professor Tim Spiller, Director of the Quantum Communications Hub, explained that there were two broad approaches to protecting encrypted information from attack by a quantum computer:

- sensitive information could be sent using quantum communication technologies that guaranteed detection of any interception of the message (see paragraphs 12 and 13 of this Report); or
- the conventional mathematical techniques used to encrypt information against attack from existing computers could be replaced with "evolved" techniques that sought to be immune from attack by conventional and quantum computers.[296]

Professor Morton agreed that, despite its high profile, the problem of digital security was unlikely to pose an insurmountable challenge.[297] However, he qualified that:

> Better awareness in industry that [standard Internet security methods] will be broken over the coming years is important, and I do not think that people are sufficiently aware of that. We should do more to support the adoption of post-quantum methods, and increasing awareness of those methods.[298]

102. Professor Spiller warned that future quantum computers already posed a threat to data that requires long-term security since "information that is sent encrypted at the moment can be stored and decrypted in the future".[299] Examples of such data included information relating to national security, medical data and other personal information. Professor Spiller told us that although neither of the two approaches to providing protection against quantum computers were yet ready for large-scale deployment, the security community would be "well positioned" to implement them once quantum communications technologies were more commercially viable and the development of mathematical methods for quantum-safe encryption were more advanced.[300] On the latter point, he highlighted a competition administered by the US National Institute of Standards and Technology aiming to determine new, standardised methods for providing digital security that would be safe against conventional and quantum computers, which he said he expected to conclude in 2019.[301]

103. **As with most new technologies, quantum technologies present a variety of potential benefits and risks to society. The future development of quantum computers could undermine the methods currently used to keep sensitive digital information secure. If the encryption methods used to secure communications over the Internet and other systems were to become vulnerable, this would have significant economic and societal impact. Ongoing work, involving quantum communications systems and 'post-quantum' cryptography methods, is expected to be able to provide technical solutions to this problem. However, there is a concern that low awareness of the problem could hinder timely implementation of such solutions.** ***The Government should monitor the development of potential solutions to the threat of quantum computers undermining***

295 Q9
296 Q172
297 Q125
298 Q133
299 Q137
300 Q178
301 Q178; see also 'Post-Quantum Cryptography Standardization', National Institute of Standards and Technology, accessed 9 October 2018

digital security techniques, including the agreement of new security standards. It must ensure that the relevant organisations and businesses are aware of the problem and its solutions, and act to ensure the timely implementation of solutions required to guarantee the continuity of widespread digital security systems. The Government should continue to encourage and participate in international dialogue with like-minded countries to address these issues.

104. Although quantum communication systems that are immune to interception would enhance security when used for legitimate purposes, the same systems could undermine security if used to evade legal interception by law enforcement or security agencies. Professor John Morton flagged that it needed to be considered "whether un-hackable and un-interceptable communications are acceptable from a security perspective".[302] Citing a case in 2016 in which the American Government struggled to access data on a phone belonging to a terrorist, Professor Michael Pepper, representing the Royal Academy of Engineering, explained that "it is a problem with the present technology, and it will become a bit more severe when quantum cryptography enters the domestic arena".[303] Professor Spiller suggested that one way to ensure law enforcement agencies could intercept messages protected by future quantum communication technologies would be to maintain a system of "trusted nodes" within the communications network, points at which messages would transfer from one quantum communication system to another and hence temporarily lose their quantum-derived protection.[304] The organisation operating the network would control access to the trusted nodes and could provide access to law enforcement or security agencies to allow them to intercept the messages in their unprotected state at these trusted nodes. Professor Spiller argued that establishing geographical points in the communications network at which quantum communication systems would not be applied would be more secure than purposefully designing vulnerabilities in the quantum communications systems themselves:

> The moment you build a vulnerability into the system that can be unlocked then other people can unlock it too. It is better to do it with physical trusted nodes at certain places where you know you can access data.[305]

105. Beyond quantum communications technologies, Airbus told us that "quantum sensors would deliver the ability to identify submarines on the sea bed from an aircraft without global positioning systems", and said that "this will be an essential sovereign capability supporting the defence of UK".[306] However, Dr Mark Bentall, Head of Technology Development and Innovation at Airbus Defence and Space, clarified that the same technology would also "clearly" pose a threat to the UK nuclear deterrent if other nations acquired the same capability:

> Obviously submarines operate under secrecy, and that is one of their key capabilities. All the time that secrecy is maintained, their capability is maintained, but as soon as there is capability to sense clearly underwater, it is a significant problem.[307]

302 Q125
303 Q126; see also 'Apple rejects order to unlock gunman's phone', BBC News, 17 February 2016
304 Q175
305 Q175
306 Airbus (QUT0001)
307 Q280

106. In response, the Ministry of Defence told us that "given the challenges of wide-area sensing in open-ocean conditions, it is unlikely that such [anti-submarine] capabilities will provide a radical change in capability in the medium term".[308] A workshop hosted by the National Quantum Technologies Programme, examining the implications of quantum technologies for defence and national security, similarly concluded that:

> Although plausible in the future, [submarine detection] would require levels of sensitivity that are currently beyond the state of the art, and there are also operational requirements which would need to be overcome [...] so that realising this in practice would be a huge challenge.[309]

The Ministry of Defence assured us that it "continues to identify, develop and assess technologies which can be used to both find and hide submarines", with particular alertness to quantum technologies afforded by the department's close relationship with the National Quantum Technologies Programme.[310]

107. **Quantum technologies have important implications for national security as well as for economic prosperity.** ***The Government must ensure that the second phase of the National Quantum Technologies Programme gives equal priority to benefitting the UK's national security and its prosperity. There should be good co-ordination between military and civil aspects of future quantum technologies in all components of the second phase of the National Programme.***

Responsible research and innovation

108. In order to manage the societal impacts of new technologies, the National Quantum Technologies Programme has adopted a Responsible Research and Innovation (RRI) framework, which UKRI told us was a "well-developed stream of work".[311] The Networked Quantum Information Technologies Hub reported in 2016 that "in comparison with RRI in some other areas of science and technology, there has been less attention, to date, given to quantum technologies".[312] The Hub has subsequently led the National Programme's RRI activity since 2017.[313] It has said that RRI should entail "a varied range of multi-level activities undertaken by multiple actors across the research and innovation lifecycles", including:

- dedicated interviews and focus groups with researchers, led by RRI specialists;
- workshops addressing key issues, involving researchers and other stakeholders;
- production of technology and risk assessments;
- public engagement activities; and
- engagement with industry, civil society and other key communities.[314]

308 Ministry of Defence (QUT0029), para 3

309 National Quantum Technologies Programme, 'Responsible Innovation in Quantum Technologies applied to Defence and National Security' (2018), p12

310 Ministry of Defence (QUT0029), para 4

311 UK Research and Innovation (QUT0023), para 38

312 Networked Quantum Information Technologies Hub, 'Thinking Ahead to a World with Quantum Computers: The Landscape of Responsible Research and Innovation in Quantum Computing' (2016), p5

313 Networked Quantum Information Technologies Hub, 'Annual Report 2017' (2017), p40

314 Networked Quantum Information Technologies Hub, 'Thinking Ahead to a World with Quantum Computers: The Landscape of Responsible Research and Innovation in Quantum Computing' (2016), pp18 and 80–82

The Networked Quantum Information Technologies Hub's director, Professor Ian Walmsley, told us that:

> [The Responsible Research and Innovation framework] is intended to engage with publics of various kinds to understand how quantum technologies, in particular quantum computing, are perceived, and to inform the public about what we are undertaking and how the field is evolving worldwide.[315]

In keeping with this aim, a 'public dialogue' exercise was commissioned in 2017 that involved 77 members of the public, each of whom attended two day-long workshops that explored the participants' knowledge, hopes and concerns regarding quantum technologies—one workshop held before and one held after an engagement activity with one of the National Quantum Technology Hubs (such as a tour of a laboratory and a lecture on quantum technologies).[316] A report summarising the findings from this exercise concluded that there was low initial public awareness of what quantum technologies were, but that overall support for the development of quantum technologies grew as people's understanding increased, provided that research was subject to proportionate governance mechanisms.[317] In addition to the public dialogue exercise, the Hubs have hosted or participated in a variety of other public outreach events to raise public awareness of quantum technologies.[318]

109. The output of RRI-focused work beyond public engagement, however, seems less extensive. The Networked Quantum Information Technologies Hub is the only Hub whose latest annual report mentions any RRI activity other than public outreach.[319] The Networked Quantum Information Technologies Hub's annual report does list a varied RRI work programme involving or directed at researchers working on quantum technologies, including training workshops, conference talks and the development of online resources.[320] The Hub has also published a white paper examining the RRI implications of quantum technologies for defence and national security, which it intends to follow with a paper on the implications for artificial intelligence.[321] However, it is not clear what proportion of the UK quantum technologies research community this work programme reaches, or what requirement there is for all researchers to demonstrate that they have properly considered the potential societal impacts of their research. Indeed, Professor Walmsley painted a mixed picture of the extent to which RRI had become embedded in research culture:

315 Q234

316 EPSRC, 'Quantum Technologies Public Dialogue Report' (2018), pp6–7

317 EPSRC, 'Quantum Technologies Public Dialogue Report' (2018), pp2–4

318 For example, see: Networked Quantum Information Technologies Hub, 'Annual Report 2018' (2018), pp42–45; Quantum Communication Hub, 'Annual Report 2016–17' (2017), pp30–31; Quantum Technology Hub for Sensors and Metrology, 'Annual Report 2015–16' (2017), p52; QuantIC, 'Annual Report 2015–16' (2016), p35

319 Quantum Communications Hub, 'Annual Report 2016–17' (2017); Quantum Technology Hub for Sensors and Metrology, 'Annual Report 2015–16' (2017); QuantIC, 'Annual Report 2015–16' (2016); these Hubs did not mention RRI activity beyond public outreach in their evidence to our inquiry either—QuantIC (QUT0002); Quantum Communications Hub (QUT0009); Quantum Technology Hub for Sensors and Metrology (QUT0013)

320 Networked Quantum Information Technologies Hub, 'Annual Report 2018' (2018), p41

321 Networked Quantum Information Technologies Hub, 'Responsible Innovation in Quantum Technologies applied to Defence and National Security' (2018); Networked Quantum Information Technologies Hub, 'Annual Report 2018' (2018), p41; Although all of the Quantum Technology Hubs are listed in this document, all three authors are affiliated with the Networked Quantum Information Technologies Hub—'Responsible Research and Innovation in Networked Quantum IT', University of Oxford, accessed 15 November 2018

> It is certainly becoming part of the culture, but the scale of the programme and the focus of going beyond research to technology development has meant that we have had to change awareness among researchers, as well as among external partners, about what it means and its implications. People have begun to embrace and understand that.[322]

Professor Delpy, Chair of the National Programme's Strategic Advisory Board, assured us that:

> We have made sure that, as part of their programme description, all the researchers in the Hubs identify the potential social implications of their research. We are open about that and try either to address it or to put in place any mitigations that are needed.[323]

However, he told us that this work had not yet uncovered "any adverse impacts that we have had to address".[324]

110. The Networked Quantum Information Technologies Hub's 2016 review of responsible research and innovation (RRI) emphasised that "RRI is a shared responsibility":

> Scientists have a responsibility which comes from being in the forefront of research […] and from their special expertise, but governments, funders, industrial partners, and early adopters of technology have at least as large a role to play.[325]

Those working at or interacting with Innovation Centres will be focused on the development of quantum technologies for real-world application, and will therefore be well-placed to assist researchers in considering the potential societal impacts of different quantum technologies.

111. **Public engagement is an important aspect of managing the societal impacts of new technologies, and we commend the National Quantum Technologies Programme for its work on this front. However, potential societal impacts must also be rigorously considered by experts working on the technology. The Networked Quantum Information Technologies Hub is producing white papers on the RRI implications of quantum technologies for different application areas. However, RRI activities in the other Hubs appear to focus almost exclusively on public outreach. Given the significant anticipated applications of quantum technologies, we are concerned to hear that the National Quantum Technologies Programme has not yet identified any potential adverse societal impacts that have had to be addressed.**

112. ***The National Quantum Technologies Programme's Responsible Research and Innovation (RRI) work should continue into a second phase of the National Programme. All of the National Quantum Hubs should identify an RRI lead responsible for co-ordinating RRI work across the Hub and to act as the primary point of contact for internal and external stakeholders on RRI matters within six months of this Report's publication. Each Hub should publish a review of the potential societal impacts of***

322 Q237
323 Q12
324 Q12
325 Networked Quantum Information Technologies Hub, 'Thinking Ahead to a World with Quantum Computers' (2016), p78

quantum technologies in their sector within a year of this Report being published, to be updated annually. These reviews should contain summaries for policymakers, describing potential implications and outlining possible measures to maximise the potential positive impacts and mitigate any negative impacts. The drafting process for these reports should involve researchers at all career stages, and be supported through training, conferences and workshops.

113. ***Innovation Centres should contribute to the National Quantum Technologies Programme's responsible research and innovation (RRI) programme of work. Each Innovation Centre should appoint an RRI lead, similar to those to be appointed at the Hubs. The Innovation Centres should be actively engaged in all relevant Hubs' annual reviews of the potential societal impacts of quantum technologies.***

114. In October 2018, the Australian Strategic Policy Institute, a defence-oriented think tank, published a report examining the problem of international research collaboration that could potentially threaten national security.[326] It focused on the Chinese People's Liberation Army's supposed policy of "picking flowers in foreign lands to make honey in China"—the practice of sending Chinese researchers, often with an obscured military affiliation, to collaborate with universities in countries in the 'Five Eyes' network or in the EU in order to gain expertise in research areas of relevance to defence or national security that can then be taken back to China.[327] The Australian Strategic Policy Institute noted that around 2,500 scientists had been sponsored by the Chinese military to travel to these countries as students or visiting scholars since 2007, with the number of scientific papers co-authored by Chinese military-affiliated authors and foreign authors rising steadily from 95 in 2007 to 734 in 2017.[328] Using co-authored publications as a proxy for the extent of collaboration, UK institutions had the most engagement with Chinese military-affiliated researchers between 2012 and 2017.[329] Quantum physics and its applications, such as in cryptography and navigation technology, were highlighted as fields in which this had been most prominent. In particular, the report warned that "while foreign universities' ties with the People's Liberation Army have grown, it isn't clear that universities have developed an understanding of the People's Liberation Army and how their collaboration with it differs from familiar forms of scientific collaboration".[330] The Australian Strategic Policy Institute made a series of recommendations in light of its findings, including:

- to raise awareness among universities and businesses of the potential risks of collaboration with scientists affiliated with the People's Liberation Army, and how such affiliations may be masked;
- to ensure information sharing between defence, intelligence, export control and immigration agencies as well as among international partners regarding scientific collaboration with the People's Liberation Army, in particular where there are any cases of deception;

326 Australian Strategic Policy Institute, 'Picking flowers, making honey: The Chinese military's collaboration with foreign universities' (2018)

327 The 'Five Eyes' network comprises the intelligence communities of the USA, the UK, Canada, Australia and New Zealand—'UKUSA Agreement Release: 1940–1956', US National Security Agency, accessed 13 November 2018

328 Australian Strategic Policy Institute, 'Picking flowers, making honey: The Chinese military's collaboration with foreign universities' (2018), p4

329 Australian Strategic Policy Institute, 'Picking flowers, making honey: The Chinese military's collaboration with foreign universities' (2018), p8

330 Australian Strategic Policy Institute, 'Picking flowers, making honey: The Chinese military's collaboration with foreign universities' (2018), p5

- for robust scrutiny of visa applications by foreign military personnel; and
- to regulate scientific training given to foreign military personnel and regulate funding awarded for scientific collaboration with non-allied militaries.[331]

115. **Concerns have been raised about the potential threats to national security arising from collaboration between UK researchers and researchers affiliated with foreign militaries.** ***Training in the potential threats arising from collaboration with researchers affiliated with foreign militaries, and the methods that can be used to obscure affiliation, should be included as part of the National Quantum Technology Programme's responsible research and innovation framework. In its response to this Report, the Government should set out what analysis it has made of the potential threat, what action it is consequently taking, what it expects of universities, businesses and other organisations with regards to managing collaborations with researchers affiliated with foreign militaries, and what support or guidance it is offering to universities to help them counter any potential threat.***

Foreign direct investment

116. The 2015 National Security Risk Assessment identified growing risks to the UK's national security, including:

- the resurgence of state-based threats and intensifying wider state competition;
- the proliferation and growing importance of technology; and
- the erosion of the rules-based international order, making it harder to tackle global threats.[332]

In 2017, the Government additionally stated that national security challenges "now exist in an increasingly complex international economic and political landscape, with greater interconnectivity of nations and ever greater flows of capital" and acknowledged that "foreign control of [UK] businesses […] increasingly raises national security concerns".[333] It has outlined a variety of ways in which foreign control of UK business could threaten national security:

- increased access to businesses, physical assets, people, operations or data could facilitate espionage;
- control over businesses, physical assets or intellectual property (such as the computer code used to run an asset) that provide a critical service could enable foreign entities to undertake disruptive or destructive actions or increase the impact of such action; and
- investments could be exploited to adversely dictate or alter services or ownership could be used as inappropriate leverage in other negotiations.[334]

331 Australian Strategic Policy Institute, 'Picking flowers, making honey: The Chinese military's collaboration with foreign universities' (2018), pp18–20
332 National Security Strategy and Strategic Defence and Security Review 2015, paras 3.1–3.4 and 3.23–3.35
333 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: The Government's review of the national security implications of foreign ownership or control' (2017), paras 48 and 72
334 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: The Government's review of the national security implications of foreign ownership or control' (2017), para 46; Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), paras 3.51–3.54

117. The Enterprise Act 2002 allows the Government to intervene in "relevant merger situations", in which two enterprises are brought under common ownership or control.[335] Such control could consist of the acquisition of majority voting rights in an enterprise, but also more subtle situations of material influence, such as minority shareholdings, representation at board-level or certain financial or other arrangements.[336] However, in 2017, the Government stated that it "[lacked] comprehensive statutory powers in relation to business ownership and control".[337] Correspondingly, amendments to the Enterprise Act 2002 were made by secondary legislation in 2018 to reduce the thresholds required for the Government to be able to intervene in mergers between domestic and foreign enterprises active in specific areas of the economy. Given the potential military uses of quantum technologies (as described in paragraphs 101 to 107 of this Report), these areas of the economy explicitly included "the development and production of quantum technology".[338]

118. Despite these amendments, the Government has since repeated that:

> The UK's current powers to prevent or mitigate [hostile exploitation of acquisition of control or influence over UK entities or assets] are no longer sufficient in light of the risks posed by national security, technological and economic changes.[339]

The Government has therefore proposed new primary legislation to reform the powers it has for preventing hostile actors from using ownership of, or influence over, businesses and assets to harm national security.[340] The proposed legislation is based on a consultation that the Government held in 2017, which set out three potential options:

- an expanded set of business transactions that the Government could "call-in" for review, to examine on national security grounds;
- a mandatory notification regime for foreign investment into the provision of "essential functions" in the economy (for example in the civil nuclear and defence sectors, or in specific businesses, assets or projects); or
- a combination of the two.[341]

335 Enterprise Act 2002, Part 3

336 Enterprise Act 2002, sections 23 and 26—see also: Department for Business, Energy and Industrial Strategy, 'Enterprise Act 2002: Changes to the Turnover and Share of Supply Tests for Mergers—Guidance 2018' (2018); Competition and Markets Authority, 'Mergers—the CMA's jurisdiction and procedure' (2014), pp15–36

337 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: The Government's review of the national security implications of foreign ownership or control' (2017), para 43

338 Enterprise Act 2002 (Share of Supply Test) (Amendment) Order 2018 (SI 2018/578) and the Enterprise Act 2002 (Turnover Test) (Amendment) Order 2018 (SI 2018/593); Department for Business, Energy and Industrial Strategy, 'Enterprise Act 2002: Changes to the Turnover and Share of Supply Tests for Mergers—Guidance 2018' (2018), pp13–24

339 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), p20

340 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018)

341 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: The Government's review of the national security implications of foreign ownership or control' (2017), paras 114–140

The Government reported that the consultation revealed "narrowly, more support for an expanded call-in power rather than a mandatory notification regime" with "very little support for the combined option".[342] There were two principal arguments against a mandatory notification regime.[343] First, a mandatory approach would require clear definitions of which transactions would require notification, which it was felt would provide less flexibility in the context of a rapidly changing environment and would require frequent amendments to the regulations setting out the scope of the notification regime. Second, the notification and screening processes involved in a mandatory approach was felt by some to represent an unreasonable burden, for businesses as well as the Government, especially given the very small proportion of business transactions that are expected to have any impact upon national security.[344] The combination of an expanded call-in regime with a mandatory notification requirement was felt to involve the burden to business and Government of a mandatory regime without reducing the uncertainty for business over which transactions could be called-in by the Government (given that the mandatory notification requirement was intended to apply only to a subset of the expanded transactions liable to be called-in).[345]

119. The Government therefore pursued a voluntary notification regime in its proposed legislation, which set out plans to:

- remove the thresholds on the turnover of the acquired company and the share of market supply of the merging enterprises required for the Government to be able to intervene;
- reduce the threshold on the percentage of voting rights that the acquiring enterprise has following the transaction, from 50% to 25% (although the current and proposed regimes both recognise other ways in which influence can be gained, beyond shares or voting rights);
- broaden the scope of the legislation to include the acquisition of influence over "entities" rather than just "enterprises"—entities will not be defined exhaustively but an indicative list will be published; and
- expand the scope of the legislation to include the acquisition of shares of, or influence over, "assets" (defined as real and personal property, intellectual property and contractual rights).[346]

342 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), p26

343 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), paras 2.14–2.16

344 Richard Harrington MP, Parliamentary Under-Secretary of State for Business and Industry, has said that there have been eight interventions on national security grounds under the regime established by the Enterprise Act 2002, from "literally thousands of [merger and acquisition] transactions"—Oral evidence taken before the Business, Energy and Industrial Strategy Committee and the Defence Committee on 30 October 2018, HC (2017–19) 1640, Q5

345 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), para 2.13

346 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), paras 24–27, 3.11, 3.12, 3.19–3.23, 3.51–3.74; Competition and Markets Authority, 'Mergers: Guidance on the CMA's jurisdiction and procedure' (2014), paras 4.1–4.30

120. Although the responses to the consultation favoured, narrowly, an expanded call-in regime with no mandatory notification requirement, the majority of the consultation respondents represented business interests rather than national security interests.[347] Whereas some representatives of the business community have expressed concern at the level of Government interference permitted under the proposed legislation, the Royal United Services Institute, a defence think tank, has raised concern at the current framework and suggested that "it would make sense to require self-reporting by British companies in sensitive sectors, over a certain financial threshold, [to make] the job of monitoring easier".[348] The Government's consultation document highlighted that "a reliance on voluntary notification or use of the call-in power […] carries the risk that the Government may be unaware of transactions that could raise national security concerns",[349] but the Government's summary of responses made very little reference to this issue.[350] The Government's proposals for the new regime set out relatively little detail about how the Government intended to ensure that it becomes aware of all transactions that could threaten national security in time to review them, stating only that:

> In order to ensure it becomes aware of trigger events (or potential trigger events) that may raise national security concerns, the Government will increase its resources dedicated to 'market monitoring' and invest in the tools and systems necessary. This additional resource will also ensure that parties, if unsure about the Government's national security interest, can engage informally with officials at an early stage in their proposed trigger event.[351]

In an exchange of correspondence, Richard Harrington MP, Parliamentary Under-Secretary of State at the Department for Business, Energy and Industrial Strategy, told us that whereas "mergers relating to publicly listed companies are announced to the market", for mergers involving private companies, the Government "may become aware [of the merger] either because it was notified by the Competition and Markets Authority, the company itself, or through other sources such as departmental relationships with the relevant sector or press reporting".[352] We note that of the countries reviewed by the UK Government in considering its options (the USA, Canada, Australia and France), all bar the USA operate a mandatory notification regime.[353]

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347 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: Summary of responses to the Government's consultation on long-term reform proposals' (2018), Annex A

348 'Britain Needs New Safeguards to Deal with Chinese Investment', Royal United Services Institute, accessed 15 November 2018; see also: 'Plan to tighten UK takeover rules are 'disproportionate'', Financial Times, 15 November 2018

349 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: The Government's review of the national security implications of foreign ownership or control' (2017), para 110

350 The risk that transactions could complete without the Government being aware of them was discussed only in relation to the Government's ability to intervene in a transaction after it had already taken place, with no firm conclusion on this given—Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: Summary of responses to the Government's consultation on long-term reform proposals' (2018), paras 50–51

351 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), para 7.14

352 Department for Business, Energy and Industrial Strategy (QUT0033)

353 Department of Business, Energy and Industrial Strategy, 'National Security and Infrastructure Investment Review: The Government's review of the national security implications of foreign ownership or control' (2017), para 65

121. **We agree with the Government that, although foreign investment in the UK is almost always benign and welcome, there is the potential for certain transactions that increase foreign influence over British entities to pose significant threats to national security. We recognise the Government's desire to avoid placing undue burden on businesses in its new regime for national security and investment. However, we are concerned that a voluntary notification regime leaves the Government unable to guarantee that it will be aware of all potential transactions that could threaten national security. The Government's consultation on this matter reported only a narrow preference against a mandatory notification regime, and did not appear to incorporate the views of the national security community. The consultation also reported little support for a combined approach, which was felt to involve the costs of the mandatory regime without providing the certainty to businesses of a purely mandatory regime. However, the costs would be limited and greater certainty would be provided if the mandatory notification regime applied to a sufficiently well-defined area of the economy. Following amendments to the Enterprise Act 2002, enterprises that research, develop, produce or supply services involving quantum technologies are already subject to a stricter foreign investment regime than most other enterprises.**

122. ***In addition to the voluntary regime for national security and investment recently proposed by the Government, we recommend that the Government establishes a mandatory notification regime for enterprises researching, developing, producing or supplying services involving quantum technologies, when they are first approached by foreign entities with offers of investment fulfilling the criteria under which the Government can currently intervene under the Enterprise Act 2002. The sanctions for not reporting a relevant merger should include criminal offences, civil financial penalties and 'director disqualification'. The National Quantum Technologies Programme, through the Hubs, Innovation Centres, new national quantum computing centre and training programmes, should raise awareness of, and provide guidance on, the mandatory notification requirements. The Government should also ensure that there is capacity within the National Programme for the provision of advice to relevant enterprises when specific cases arise.***

123. Acknowledging the fact that, under a voluntary notification regime there may be "instances where the Government only becomes aware of a trigger event that raises national security concerns after it has taken place or has completed", the White Paper's proposals provide for the Government to be able to retrospectively call in a trigger event for review within a set period after the transaction itself has occurred.[354] The proposed period for this is six months, which the Government itself notes is considerably shorter than the equivalent period under comparable regimes internationally (including those in Germany, Australia and the USA).[355] The White Paper states the Government's opinion that "it is important that the prescribed period is not unnecessarily lengthy, in order to reduce uncertainty for parties to a trigger event", but it does not provide any justification for this period to be significantly shorter in the UK than in other comparable jurisdictions.

354 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), paras 6.26–6.35

355 Secretary of State for Business, Energy and Industrial Strategy, 'National Security and Investment: A consultation on proposed legislative reforms' (2018), paras 6.31–6.32

Responding to our enquiries, the Business and Industry Minister simply told us that "each [of the other international regimes] has been developed under a different legal framework, while some are based on voluntary notification and others on mandatory notification".[356]

124. **In situations that would be subject to a voluntary notification regime (for example where enterprises do not work with quantum technologies, or where transactions involving enterprises working with quantum technologies fall outside of the merger situations covered under the Enterprise Act 2002), it is possible that the Government will learn of a transaction that threatens national security after the transaction has completed. It is important that the Government is still able to act to protect national security in these cases. A time limit within which the Government could retrospectively intervene once it learns of a transaction would also incentivise enterprises who consider a transaction to be a potential threat to national security to notify the Government of it, without impacting upon enterprises involved in transactions that are clearly of no threat to national security. The Government's proposed legislation includes such a period of six months—significantly shorter than the duration of equivalent periods in comparable regimes in other countries. The fact that equivalent periods are significantly longer across a diversity of comparable international regimes appears to be an argument for the UK to adopt a longer period, rather than, as the Business and Industry Minister suggested, a reason to not.**

125. ***We recommend that, wherever the proposed voluntary notification regime applies, the Government increases the period in which it can retrospectively intervene in business transactions, as a result of national security concerns, to five years, in line with other countries such as Germany. This would allow the Government a greater window to intervene where it is not notified of relevant transactions. This time limit should be reviewed, and amended if necessary, after five years, to see if it has been used and to see if it has placed burden on business.***

356 Department for Business, Energy and Industrial Strategy (QUT0033)

Conclusions and recommendations

Quantum Technologies and their Applications

1. Quantum technologies offer the potential for significant economic growth and improved capabilities across multiple industry sectors. The first phase of the National Quantum Technologies Programme has placed the UK in a world-leading position. The Government announced £235m of funding for quantum technologies in the 2018 Budget, taking total funding for the next phase of the National Quantum Technologies Programme to £315m. We welcome the Government's decision to support a second phase of the National Quantum Technologies Programme with this funding, which is broadly commensurate with the Strategic Advisory Board's estimated requirements. (Paragraph 26)

Continuing the National Programme—Governance

2. Although the first phase of the National Quantum Technologies Programme is widely seen to have been successful, we believe that there is room for improvement in the co-ordination across the Programme as it moves into a second phase, in particular between its more academically-focused and its more commercially-focused activities. (Paragraph 31)

3. The governing body of the second phase of the National Quantum Technologies Programme should engage with, and seek guidance from, academia, industry, regulators, standards bodies and Government bodies overseeing national security and defence. Industry should have a strong collective influence on the decisions of the governing body, in keeping with the increased role and investment expected of industry as quantum technologies achieve market readiness. (Paragraph 35)

4. We have heard strong support from across the UK quantum technologies community for the establishment of a new governance structure for the second phase of the National Quantum Technologies Programme. *The Government should establish a new Executive Board to oversee the second phase of the National Quantum Technologies Programme within three months of this Report's publication. The new Board should have the power to make decisions over the delivery of the second phase of the National Programme, and a corresponding level of control over the funding allocated to the next phase of the National Programme. It should have a clearly defined mission statement and be held accountable for delivering on it. The mission statement should include an overall aim to support the development of a UK quantum technologies industry that delivers the maximum economic, national security and societal benefit for the UK public as a whole. The new Board should comprise representatives from academia, small and medium-sized enterprises, large companies, standards bodies, regulators and the Government, including from national security and defence organisations.* (Paragraph 38)

5. *The Executive Board should produce a detailed roadmap, or series of roadmaps, for the future potential markets for quantum technologies in the UK, in consultation with appropriate experts from the market sectors identified. The roadmap should assess the likely size and timeframe of each potential market, as well as the technological*

developments, infrastructure, workforce, supply chains and regulatory measures that are expected to be required to harness each market opportunity. The roadmap should cover the next twenty years and be updated annually. It should be publicly available, with a first iteration completed within one year of this Report's publication. (Paragraph 42)

6. *The Executive Board should use the roadmap(s) of future quantum technology markets to identify potential obstacles to the development and commercialisation of quantum technologies in the UK and to define a strategy to overcome these. The strategy should be published and updated alongside the roadmap and include clear, measurable milestones, to be reviewed annually.* (Paragraph 43)

Continuing the National Programme—Innovation Centres

7. We agree with UK Research and Innovation that the establishment of Innovation Centres is a "priority" for the National Programme going forward. The announcements made confirming the extension of the National Quantum Technologies Programme into a second phase did not, however, reference Innovation Centres and proposed something comparable only in the quantum computing domain. Although the new quantum computing centre is welcome, it is worth noting that quantum computing is the quantum technology furthest from market. The drive to advance technologies from the existing Hubs towards greater market readiness—for example, through an Innovation Centre or Innovation Centres—would therefore appear to be most urgent for other quantum technologies. (Paragraph 51)

8. *The second phase of the National Quantum Technologies Programme should establish Innovation Centres to provide access to facilities for developing, manufacturing, testing and validating quantum technologies, as well as to act as focal points around which collaboration and supply chains can consolidate. This will require Innovation Centres to exist, at least in part, as physical centres rather than as 'virtual networks'. Reflecting the need for Innovation Centres to focus on the development of commercial products, Innovation Centres should target specific market sectors rather than reflecting the different types of quantum technologies, although multiple sector-specific Innovation Centres could co-occupy sites where they require the same shared technical facilities. While we support the use of suitable existing infrastructure to house Innovation Centres where it can deliver what is required more quickly and at a reduced cost, this should not dilute the concept of Innovation Centres or weaken the drive to establish them as soon as possible. In its response to this Report, the Government should confirm its intention to set up Innovation Centres and outline how many it intends to establish, which sectors they will cover and what the timeline is for their establishment. The Executive Board must ensure that there is good co-ordination between the new Innovation Centres and the Hubs and ensure that technologies are supported through research, development and commercialisation and to provide strategic oversight so that activities in Innovation Centres and Hubs complement each other.* (Paragraph 52)

9. The proposed Innovation Centres bear resemblance to the Catapult Centres that already exist. The Government, UK Research and Innovation, and the new Executive Board of the National Quantum Technologies Programme should ensure that the planning of Innovation Centres incorporates lessons learned from the experience

and assessment of the Catapult Centres. The Innovation Centres should have clear purpose statements, measurable objectives and be subject to periodic performance assessment. (Paragraph 54)

10. We welcome the Government's decision to fund a new national centre for quantum computing. *The new national quantum computing centre should focus on the development of software for quantum computers as well as hardware.* (Paragraph 56)

Continuing the National Programme—Funding

11. It is right that the Government should look to industry to contribute to funding for technology development, especially as quantum technologies grow closer to commercialisation. However, it is important that matched funding requirements do not prevent important work from going ahead. Other funding rules, such as the 30% limit on project funding awarded to non-commercial organisations, can also restrict the scope of some projects. (Paragraph 66)

12. *Innovate UK should ensure that there is flexibility in rules where State Aid rules and other relevant regulations allow it, and design the rules applying to funding calls around the aims of the project rather than designing projects around the standard rules. In particular, the 30% limit on funding that can be awarded to non-commercial organisations should be relaxed where it hampers applications for funding calls or the scope of the projects funded. UK Research and Innovation should monitor the impact of any matched funding requirements and ensure that such conditions do not detriment the development of quantum technologies in the UK. It should take into account 'in-kind' contributions (such as time, access to facilities or training) from industry rather than pure investment alone, and continually review the funding environment in the UK compared to other quantum technology programmes internationally, to ensure that the UK remains competitive. The Government should prioritise spending on initiatives or capital that will benefit the development of the wider UK quantum technologies industry alongside those projects that will encourage co-investment from industry.* (Paragraph 67)

13. *UK Research and Innovation, in co-operation with the new Executive Board, should regularly review the funding available to fundamental research in quantum science. As the Government aims to increase spending on research and development to 2.4% of GDP, and as the National Quantum Technologies Programme develops the application and commercialisation of quantum technologies, the Government should be ready to provide the funding required to ensure fundamental research keeps pace. UK Research and Innovation should additionally ensure that projects of a variety of scale and duration are funded, to ensure that opportunities exist for organisations of all sizes.* (Paragraph 68)

14. Awareness across industry of the potential for quantum technologies, in particular in the short-term, needs to be improved. *The new Executive Board should engage with businesses and industry bodies that are not yet actively pursuing opportunities presented by quantum technologies, articulating the near-term capabilities expected of such technologies and investigating what specific product requirements and technology demonstrations are needed to drive uptake in different sectors. This activity should*

aim to raise industrial awareness of quantum technologies and feed into the Executive Board's roadmap and strategy for developing the UK quantum technologies industry. (Paragraph 73)

15. We commend the Ministry of Defence on its support for quantum technology demonstrator projects. Similar opportunities exist for other Government departments to support the development of quantum technology products that they would benefit from, with the added advantage of assisting the nascent UK quantum industry by demonstrating the value of quantum technologies to other potential end-users. *In collaboration with the Chief Scientific Adviser network, the new Executive Board of the National Quantum Technologies Programme should identify opportunities for Government Departments to support quantum technology demonstrator projects and encourage their uptake by assessing the positive impacts that such projects could achieve for the Department and for the UK quantum technologies industry, if successful.* (Paragraph 74)

16. We agree with the Connell Review that the Small Business Research Initiative has a "unique and valuable role to play in the innovation and procurement landscape", supporting UK businesses in developing innovative new products while enabling public sector bodies to source innovative solutions to the challenges they face. However, the Government's response to the Connell Review so far appears limited. The GovTech Catalyst only supports public bodies in sourcing digital technology solutions and the three-year, £20m GovTech Fund is significantly smaller than the £250m that the Connell Review recommended to be spent per annum through SBRI, or the £200m target the Government had for SBRI spending in 2014–15. *We recommend that the Government fully adopts the recommendations of the Connell Review, and establishes a central SBRI fund with a National Board to oversee its delivery as part of the 2019 Spending Review.* (Paragraph 78)

17. Quantum technologies promise significant opportunities for UK economic growth as well as improvements to Government departments' capabilities. Quantum technologies are therefore particularly well-suited to the aims and implementation of the Small Business Research Initiative. *We recommend that the Government establishes a QuantumTech Catalyst to drive public sector organisations' use of the Small Business Research Initiative for quantum technologies, in the same way that the GovTech Catalyst has for digital technologies. The new QuantumTech Catalyst should seek to launch a first round of challenges within six months of this Report's publication.* (Paragraph 79)

Continuing the National Programme—Skills

18. There is significant concern in the quantum technology community that the future development of quantum technologies in the UK could be constrained by the lack of a suitably skilled workforce. This skills shortage is not unique to the UK, and the existing training programmes provided under the National Quantum Technologies Programme are well-regarded, but increasing and improving the training offered must be a priority for the second phase of the National Programme. (Paragraph 88)

19. *The Government should continue and expand the National Quantum Technologies Programme's current training programmes. The new Executive Board, in co-operation*

with UKRI, should engage with companies working on quantum technologies or closely related fields to help tailor the content of doctoral training programmes to ensure that they provide the balance of skills needed by industry. This will require exposure to commercial practices and requirements, which could be provided through secondments, industry-led projects during the first year of a Centre for Doctoral Training course or industry-proposed and sponsored PhD projects. This should be completed in time for renewal of the Centres for Doctoral Training next year. Furthermore, UKRI should find ways to make the terms on which industry can input into training programmes more flexible, to facilitate increased engagement (for example by enabling input outside of the five-year funding cycles of Centres for Doctoral Training). In exchange, UKRI should seek contributions from industry to fund additional studentships. The Government should be ready to co-invest where industry funding is available. (Paragraph 89)

20. The future workforce required for a successful UK quantum technologies industry will not be composed entirely of PhD-level graduates and above. Although workers at lower qualification levels may not need skills as specifically tailored to quantum technologies as for those with higher qualifications, the growth of a quantum technologies industry will add to the demand for engineering and scientific graduates, technicians and apprentices. In addition to training being required for those entering the workforce, we believe that it is also required for engineers, technicians and others already in the workforce. (Paragraph 94)

21. *The second phase of the National Quantum Technologies Programme must ensure that appropriate training is available at undergraduate, technician and apprenticeship level, alongside continued provision at PhD level. It should provide training opportunities for established workers as well as for those entering the workforce, for example through continuing professional development modules or short university-based courses, in a manner that is easy for companies to access. There should also be periodic, sector-specific workshops available to end-users of quantum technologies, with the aim of growing a network of quantum 'champions' in sectors where quantum technologies can already start to be applied. These modules, courses and workshops should all be available within three years of the publication of this Report.* (Paragraph 95)

22. *The new Executive Board should engage with companies to ensure, facilitate and co-ordinate input from quantum technologies enterprises—both large companies and small and medium-sized enterprises—into the Institute for Apprenticeships' ongoing work on the development of apprenticeship standards and the 'health and science' and 'engineering and manufacturing' T levels. This endeavour should ensure that these training routes: flag the opportunity of the quantum technologies sector to students; cover the basic skills that enterprises working with quantum and related technologies require; and offer apprenticeships or work placements with enterprises working in the quantum sector. The Executive Board should encourage and support quantum technology enterprises to offer apprenticeship places and work placements.* (Paragraph 96)

The societal implications of quantum technologies

23. As with most new technologies, quantum technologies present a variety of potential benefits and risks to society. The future development of quantum computers could undermine the methods currently used to keep sensitive digital information secure. If the encryption methods used to secure communications over the Internet and other systems were to become vulnerable, this would have significant economic and societal impact. Ongoing work, involving quantum communications systems and 'post-quantum' cryptography methods, is expected to be able to provide technical solutions to this problem. However, there is a concern that low awareness of the problem could hinder timely implementation of such solutions. *The Government should monitor the development of potential solutions to the threat of quantum computers undermining digital security techniques, including the agreement of new security standards. It must ensure that the relevant organisations and businesses are aware of the problem and its solutions, and act to ensure the timely implementation of solutions required to guarantee the continuity of widespread digital security systems. The Government should continue to encourage and participate in international dialogue with like-minded countries to address these issues.* (Paragraph 103)

24. Quantum technologies have important implications for national security as well as for economic prosperity. *The Government must ensure that the second phase of the National Quantum Technologies Programme gives equal priority to benefitting the UK's national security and its prosperity. There should be good co-ordination between military and civil aspects of future quantum technologies in all components of the second phase of the National Programme.* (Paragraph 107)

25. Public engagement is an important aspect of managing the societal impacts of new technologies, and we commend the National Quantum Technologies Programme for its work on this front. However, potential societal impacts must also be rigorously considered by experts working on the technology. The Networked Quantum Information Technologies Hub is producing white papers on the RRI implications of quantum technologies for different application areas. However, RRI activities in the other Hubs appear to focus almost exclusively on public outreach. Given the significant anticipated applications of quantum technologies, we are concerned to hear that the National Quantum Technologies Programme has not yet identified any potential adverse societal impacts that have had to be addressed. (Paragraph 111)

26. *The National Quantum Technologies Programme's Responsible Research and Innovation (RRI) work should continue into a second phase of the National Programme. All of the National Quantum Hubs should identify an RRI lead responsible for co-ordinating RRI work across the Hub and to act as the primary point of contact for internal and external stakeholders on RRI matters within six months of this Report's publication. Each Hub should publish a review of the potential societal impacts of quantum technologies in their sector within a year of this Report being published, to be updated annually. These reviews should contain summaries for policymakers, describing potential implications and outlining possible measures to maximise the potential positive impacts and mitigate any negative impacts. The drafting process for these reports should involve researchers at all career stages, and be supported through training, conferences and workshops.* (Paragraph 112)

27. *Innovation Centres should contribute to the National Quantum Technologies Programme's responsible research and innovation (RRI) programme of work. Each Innovation Centre should appoint an RRI lead, similar to those to be appointed at the Hubs. The Innovation Centres should be actively engaged in all relevant Hubs' annual reviews of the potential societal impacts of quantum technologies.* (Paragraph 113)

28. Concerns have been raised about the potential threats to national security arising from collaboration between UK researchers and researchers affiliated with foreign militaries. *Training in the potential threats arising from collaboration with researchers affiliated with foreign militaries, and the methods that can be used to obscure affiliation, should be included as part of the National Quantum Technology Programme's responsible research and innovation framework. In its response to this Report, the Government should set out what analysis it has made of the potential threat, what action it is consequently taking, what it expects of universities, businesses and other organisations with regards to managing collaborations with researchers affiliated with foreign militaries, and what support or guidance it is offering to universities to help them counter any potential threat.* (Paragraph 115)

29. We agree with the Government that, although foreign investment in the UK is almost always benign and welcome, there is the potential for certain transactions that increase foreign influence over British entities to pose significant threats to national security. We recognise the Government's desire to avoid placing undue burden on businesses in its new regime for national security and investment. However, we are concerned that a voluntary notification regime leaves the Government unable to guarantee that it will be aware of all potential transactions that could threaten national security. The Government's consultation on this matter reported only a narrow preference against a mandatory notification regime, and did not appear to incorporate the views of the national security community. The consultation also reported little support for a combined approach, which was felt to involve the costs of the mandatory regime without providing the certainty to businesses of a purely mandatory regime. However, the costs would be limited and greater certainty would be provided if the mandatory notification regime applied to a sufficiently well-defined area of the economy. Following amendments to the Enterprise Act 2002, enterprises that research, develop, produce or supply services involving quantum technologies are already subject to a stricter foreign investment regime than most other enterprises. (Paragraph 121)

30. *In addition to the voluntary regime for national security and investment recently proposed by the Government, we recommend that the Government establishes a mandatory notification regime for enterprises researching, developing, producing or supplying services involving quantum technologies, when they are first approached by foreign entities with offers of investment fulfilling the criteria under which the Government can currently intervene under the Enterprise Act 2002. The sanctions for not reporting a relevant merger should include criminal offences, civil financial penalties and 'director disqualification'. The National Quantum Technologies Programme, through the Hubs, Innovation Centres, new national quantum computing centre and training programmes, should raise awareness of, and provide guidance*

on, the mandatory notification requirements. The Government should also ensure that there is capacity within the National Programme for the provision of advice to relevant enterprises when specific cases arise. (Paragraph 122)

31. In situations that would be subject to a voluntary notification regime (for example where enterprises do not work with quantum technologies, or where transactions involving enterprises working with quantum technologies fall outside of the merger situations covered under the Enterprise Act 2002), it is possible that the Government will learn of a transaction that threatens national security after the transaction has completed. It is important that the Government is still able to act to protect national security in these cases. A time limit within which the Government could retrospectively intervene once it learns of a transaction would also incentivise enterprises who consider a transaction to be a potential threat to national security to notify the Government of it, without impacting upon enterprises involved in transactions that are clearly of no threat to national security. The Government's proposed legislation includes such a period of six months—significantly shorter than the duration of equivalent periods in comparable regimes in other countries. The fact that equivalent periods are significantly longer across a diversity of comparable international regimes appears to be an argument for the UK to adopt a longer period, rather than, as the Business and Industry Minister suggested, a reason to not. (Paragraph 124)

32. *We recommend that, wherever the proposed voluntary notification regime applies, the Government increases the period in which it can retrospectively intervene in business transactions, as a result of national security concerns, to five years, in line with other countries such as Germany. This would allow the Government a greater window to intervene where it is not notified of relevant transactions. This time limit should be reviewed, and amended if necessary, after five years, to see if it has been used and to see if it has placed burden on business.* (Paragraph 125)

Formal Minutes

Tuesday 27 November 2018

Members present:

Norman Lamb, in the Chair

Vicky Ford
Bill Grant
Darren Jones
Stephen Metcalfe
Damien Moore
Martin Whitfield

Draft Report (*Quantum technologies*), proposed by the Chair, brought up and read.

Ordered, That the draft Report be read a second time, paragraph by paragraph.

Paragraphs 1 to 125 read and agreed to.

Summary agreed to.

Resolved, That the Report be the Twelfth Report of the Committee to the House.

Ordered, That the Chair make the Report to the House.

Ordered, That embargoed copies of the Report be made available (Standing Order No. 134).

[Adjourned till Tuesday 4 December at 9.00am

Witnesses

The following witnesses gave evidence. Transcripts can be viewed on the inquiry publications page of the Committee's website.

Tuesday 5 June 2018

Professor Sir Peter Knight, Emeritus Professor, Imperial College London, and **Professor David Delpy**, Chair of the Strategic Advisory Board, National Quantum Technologies Programme Q1–75

Jonathan Flint, President-Elect, Institute of Physics, **Professor Sir Michael Pepper**, Royal Academy of Engineering, **Professor John Morton**, Director, Quantum Science and Technology Institute, University College London, and **Dr Ashley Montanaro**, Lecturer in Applied Mathematics, University of Bristol Q76–134

Thursday 28 June 2018

Professor Erling Riis, Head of the Department of Physics, University of Strathclyde, **Dr Sara Diegoli**, Programme Manager, QuantIC, and **Professor Timothy Spiller**, Director, Quantum Communications Hub Q135–180

Dr Graeme Malcolm, CEO, M2 Lasers, **Professor Martin Dawson**, Head of the Fraunhofer Centre for Applied Photonics, Fraunhofer UK Research Ltd, and **Dr Richard Walker**, CEO, Photon Force Q181–220

Tuesday 17 July 2018

Professor Kai Bongs, Director, Quantum Technology Hub for Sensors and Metrology, **Professor Ian Walmsley**, Director, Networked Quantum Information Technologies Hub, and **Professor Winfried Hensinger**, Professor of Quantum Technologies, University of Sussex Q221–273

Professor Trevor Cross, Chief Technology Officer, Teledyne e2v, **Dr Mark Bentall**, Head of Technology Development and Innovation, Airbus Defence and Space, **Dr Andrew Shields**, Quantum Technologies R&D Lead, Toshiba Research Europe Ltd, and **Dr Peter Thompson**, Chief Executive Officer, National Physical Laboratory Q274–355

Wednesday 12 September 2018

Sam Gyimah MP, Minister for Universities, Science, Research and Innovation, Department for Business, Energy and Industrial Strategy, **Professor Sir Mark Walport**, Chief Executive, UK Research and Innovation Q356–450

Published written evidence

The following written evidence was received and can be viewed on the inquiry publications page of the Committee's website.

QUT numbers are generated by the evidence processing system and so may not be complete.

1 Airbus (QUT0001)

2 BT Group (QUT0032)

3 Department for Business, Energy and Industrial Strategy (QUT0030), (QUT0033)

4 The EPSRC Quantum Communications Hub (QUT0009)

5 EU COST action QTSpace (QUT0018)

6 Fraunhofer UK Research Ltd (QUT0021)

7 Institute of Physics (QUT0010), (QUT0034)

8 M Squared (QUT0024)

9 Manchester Metropolitan University (QUT0003)

10 Ministry of Defence (QUT0026), (QUT0029)

11 Montanaro, Dr Ashley and others (QUT0005)

12 National Physical Laboratory (QUT0017), (QUT0028)

13 Networked Quantum Information Technologies Hub (NQIT) (QUT0006)

14 PA Consulting Group (QUT0014)

15 Professor Sir Peter Knight (QUT0015)

16 QET Labs, University of Bristol (QUT0019)

17 QuantIC, University of Glasgow (QUT0002)

18 Quantum Technology Hub for Sensors and Metrology, University of Birmingham (QUT0013)

19 Royal Academy of Engineering (QUT0012)

20 Shields, Dr Andrew (QUT0020)

21 Teledyne e2v (QUT0016)

22 UCL Quantum Science and Technology Institute (UCLQ) (QUT0008)

23 UK Diamond Quantum Technology Community Informal Group (QUT0025)

24 UK Research and Innovation (QUT0023), (QUT0031)

25 University of Strathclyde (QUT0004)

26 University of Sussex (QUT0007)

List of Reports from the Committee during the current Parliament

All publications from the Committee are available on the publications page of the Committee's website. The reference number of the Government's response to each Report is printed in brackets after the HC printing number.

Session 2017–19

First Report	Pre-appointment hearing: chair of UK Research & Innovation and executive chair of the Medical Research Council	HC 747
Second Report	Brexit, science and innovation	HC 705
Third Report	Genomics and genome editing in the NHS	HC 349
Fourth Report	Algorithms in decision-making	HC 351
Fifth Report	Biometrics strategy and forensic services	HC 800
Sixth Report	Research integrity	HC 350
Seventh Report	E-cigarettes	HC 505
Eighth Report	An immigration system that works for science and innovation	HC 1061
Ninth Report	Flu vaccination programme in England	HC 853
Tenth Report	Research integrity: clinical trials transparency	HC 1480
Eleventh Report	Evidence-based early years intervention	HC 506
Thirteenth Report	Energy drinks and children	HC 821
First Special Report	Science communication and engagement: Government Response to the Committee's Eleventh Report of Session 2016–17	HC 319
Second Special Report	Managing intellectual property and technology transfer: Government Response to the Committee's Tenth Report of Session 2016–17	HC 318
Third Special Report	Industrial Strategy: science and STEM skills: Government Response to the Committee's Thirteenth Report of Session 2016–17	HC 335
Fourth Special Report	Science in emergencies: chemical, biological, radiological or nuclear incidents: Government Response to the Committee's Twelfth Report of Session 2016–17	HC 561
Fifth Special Report	Brexit, science and innovation: Government Response to the Committee's Second Report	HC 1008
Sixth Special Report	Algorithms in decision-making: Government Response to the Committee's Fourth Report	HC 1544
Seventh Special Report	Research integrity: Government and UK Research and Innovation Responses to the Committee's Sixth Report	HC 1562

Eighth Special Report	Biometrics strategy and forensic services: Government's Response to the Committee's Fifth Report	HC 1613
Ninth Special Report	An immigration system that works for science and innovation: Government's Response to the Committee's Eighth Report	HC 1661