

Science and Technology Committee

Oral evidence: [Quantum technologies](#), HC 820

Tuesday 17 July 2018

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Members present: Norman Lamb (Chair); Vicky Ford; Darren Jones; Stephen Metcalfe; Carol Monaghan; Neil O'Brien; Graham Stringer.

Questions 221 - 355

Witnesses

I: 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.

II: 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.

Written evidence from witnesses:

- [Quantum Technology Hub for Sensors and Metrology](#)
- [Networked Quantum Information Technologies Hub](#)
- [University of Sussex](#)
- [Teledyne e2v](#)
- [Airbus](#)
- [Dr Andrew Shields](#)
- [National Physical Laboratory](#)

Examination of witnesses

Witnesses: Professor Bongs, Professor Walmsley and Professor Hensinger.

Q221 **Chair:** Welcome. We are sorry to have kept you waiting; we had quite a lot of private business to get through. It is very good of you to come along. Can we start with quick introductions?

Professor Bongs: I am Professor Kai Bongs from the University of Birmingham. I am the director of the UK National Quantum Technology Hub for Sensors and Metrology, which is led by the University of Birmingham in collaboration with the Universities of Glasgow, Nottingham, Sussex, Southampton and Strathclyde, and has very strong links with NPL, DSTL and about 200 industry partners, six of which have put money into a programme of £100 million overall to drive sensors in gravity and magnetic fields, rotation, time and light to market and social benefits.

Q222 **Chair:** Can I acknowledge that we shifted this hearing from Birmingham to Westminster because of parliamentary business? Apologies to the University of Birmingham for the problems that caused. We are very grateful to the university for having offered to host us, and thank you for coming down.

Professor Walmsley: I am Ian Walmsley of the University of Oxford. I am the director of the Networked Quantum Information Technologies Hub, the objective of which is to build the core components for a scalable fault-tolerant quantum computer. Like Kai's hub, there is a large range of academic, industrial and Government partners.

Professor Hensinger: My name is Winfried Hensinger. I am professor of quantum technologies at the University of Sussex, and director of the Sussex Centre for Quantum Technologies, where we do research in a whole variety of different quantum technologies. We are part of two quantum technology hubs. I am head of Sussex Ion Quantum Technology Group, where we are developing a trapped ion quantum computer and portable quantum sensors.

Q223 **Chair:** Thank you all very much. We have quite a lot to get through. As we go through our questions, do not feel that you all have to answer everything. Can you try to keep your answers as succinct as possible? Professor Bongs, could you outline the main applications of quantum sensing and metrology technologies?

Professor Bongs: Quantum sensors, like all quantum technologies in general, could underpin a wide variety of sectors from agriculture to space. We have developed a road map and a very good channel analysis that has identified economic market potential of about £3 billion per year for quantum sensors alone. I will give two examples, one in infrastructure productivity and the other in healthcare.



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.

Q224 **Chair:** Therefore, there are enormous potential gains from this technology.

Professor Bongs: Of course. The overall potential impact on the economy would be manifold, like the market potential of sensors themselves.

Q225 **Chair:** What will a quantum computer be able to do that a conventional computer cannot do?

Professor Walmsley: Let me start by quoting Professor Bill Phillips, who won the Nobel prize in 1997. He notes that the quantum computer is as different from the modern-day computer as the modern computer is from an abacus, so it is a truly revolutionary change in computing capabilities and capacity and, therefore, it will touch on an extraordinarily wide range of applications.

A key point is that scalable fault-tolerant quantum computers will be able fully to simulate and analyse all kinds of quantum systems. This will have applications from the design and understanding of new molecules that have potential for new drugs, to the understanding of complex new quantum materials that may be relevant for magnetism, superconductivity and the delivery of power, as well as other sorts of applications across different sectors, including cryptanalysis and logistics design.

Q226 **Chair:** How certain are the applications now?

Professor Walmsley: Some of them are very well known and understood. We know that some will be important, but we do not fully have the algorithms, and in other areas, such as machine learning and artificial intelligence, we are just beginning to explore what sorts of things may be possible.

Q227 **Chair:** What is the timescale for the ones where we are most certain and for the longer-off ones?

Professor Walmsley: The first issue is, when will a fully scalable quantum computer be available? There is a very wide range of opinions on that. What you see at the moment are early-stage, accessible, small-scale, non-fault-tolerant and non-scalable computers—for example, IBM and Google, with a few tens of qubits—but I think it will be five to 10 years before the next generation of real computers begins to emerge.



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Q228 **Chair:** Will there be a further period beyond that when it has real applications that have a societal effect?

Professor Walmsley: There will be early-stage applications for non-scalable machines as co-processors for regular high-performance computers to be able to undertake certain tasks that have a specific quantum component; materials design is an example, and possibly hydrodynamics. Those are open questions at the moment, but there will be some quite early-stage wins for some key applications.

Professor Hensinger: One way to think of quantum computers is that they can solve certain problems that even the fastest supercomputers would take billions of years to calculate. They operate in an entirely different fashion from conventional computers, in that they harness quantum effects. For example, an atom can be in two different places at the same time. That is referred to as superposition and is one of the ingredients of quantum computers that makes them so special.

To understand the development of quantum computers, it is instructional to go back to the 1940s and think about the development of conventional computers. In the 1940s, we had the first conventional computers. Indeed, one could argue that their use in breaking encryption helped at least partially to decide the second world war.

At that point, all the functions that conventional computers would perform in our society were not really known. It is similar with quantum computers; for example, there is already a large number of well-known algorithms that allow us to break common RSA encryption. It is very important to know that quantum computers operate as nature does; they operate according to the laws of quantum physics, and as such there is a tremendous amount of opportunity. It is very unlikely that we fully understand all the opportunities quantum computers pose, similar to the time when we first built conventional computers.

Q229 **Neil O'Brien:** Do you think the Government are providing sufficient support for demonstrator projects in quantum outside the defence space? Are there particular projects that you think the Government should be pursuing? If you were Science Minister for a day, what projects in the quantum space would you be backing that we are not currently backing?

Professor Hensinger: It is most important that we capitalise on where the UK is world-leading. I like to stress that the first iteration of the national quantum programme was quite significant, in that it gave the UK a distinct lead in commercialising and making quantum technologies happen, so it is very important that we now build on the international lead we have. There are a few areas where we are leading, and one of those areas is quantum computing, in particular trapped ion quantum computing.

Q230 **Neil O'Brien:** Trapped ion.



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Professor Hensinger: Ions are charged atoms, and that is a particular physical platform that allows you to do quantum computing. Two leading platforms are being used right now. One of them is superconducting qubits and the other is trapped ions. The advantage of trapped ion qubits lies in the fact that this is a technology that can operate at room temperature, but, far more importantly, using this technology it is possible to build a truly powerful quantum computer. When I say it is powerful, I mean a quantum computer that has so many millions, eventually billions, of quantum bits that you can solve really interesting problems, such as understanding chemical reactions and creating new pharmaceuticals.

Last year, we published the first construction plan on how to build such a quantum computer. With the technology innovations we made as part of the national quantum technology programme, we are now able to say that it is possible to build such a machine.

Q231 **Neil O'Brien:** That is a clear answer on trapped ion quantum computing. Professor Walmsley or Professor Bongs, do either of you want to comment on what you would pursue as a particular demonstrator project?

Professor Walmsley: There are two kinds of things, and the UK ought to be pursuing both. No doubt Kai will say more about early-stage quantum technologies, but let me reflect a little bit on computing. 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. There is an intensely competitive scenario across the world at the moment, and, as Winni noted, the UK has made a very strong first play in that area.

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 quantum 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. I turn to Kai on other early-stage technologies that will come before the quantum computer is there.

Professor Bongs: We have been involved in two DSTL-funded projects: the gravity imager and the quantum navigator. These have proven extremely efficient in deeply involving the industry. There is very strong involvement by Teledyne e2v and NPL; both are building up quite large internal industry teams for quantum technologies. These are pivotal in creating engagement by industry.

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 DEFRA investing in sensors to look for river embankments in flood areas.

Q232 Neil O'Brien: The 2016 Government Office for Science report said that the Government should identify projects that "if solved by a quantum computer" would be useful demonstrators. Are you aware of what progress has been made towards the goal of identifying use cases that would be good for quantum? Has that happened or been followed through?

Professor Walmsley: Yes. The NQIT hub has modified its programme in light of that report to put more effort into identifying those applications and working with external parties to try to broaden the range of people who would use them.

Q233 Neil O'Brien: What kinds of applications have been identified?

Professor Walmsley: We have done several things. We have set up an emulator programme that allows access both to simulations or emulations on current high-performance computing and to the early-stage quantum computers that exist around the world. That is to draw in different science and research communities where algorithms will advance the science that we think will lead to big impacts, as well as bringing in user communities; for example, we have a project with a logistics company to understand how annealing and other types of algorithms can help drive more efficient logistics. We have also engaged with a number of major companies. We have partnerships with IBM, Airbus and BAE Systems, all of which are to explore new ways in which quantum computing may affect the core elements of their business.

Q234 Stephen Metcalfe: This is a potentially powerful new technology and we do not yet know where it will lead, so it is quite important that it is developed in a responsible way. Professor Walmsley, can you outline for me the responsible research and innovation framework, and how it applies?

Professor Walmsley: From the beginning of the programme, we designed into it a responsible and research innovation activity; it forms one of the core work packages of our hub. It 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.

We have been rolling out a programme across the hubs in parallel with EPSRC, which has done its own public dialogue as well. I am happy to leave you with a copy of both the EPSRC report and our annual report for this year, which on pages 41 et seq gives a detailed statement about what we have been doing in that space. The main conclusions are that people are predominantly excited about the notion of quantum and the



possibilities it offers. The concerns are around who will own it, how it will be controlled and what sort of applications it will, possibly, be used for.

Q235 **Stephen Metcalfe:** Are those questions answered as part of the RRI discussions? I think you have held workshops.

Professor Walmsley: Yes, we have. They are certainly being addressed. As Winni said, we do not yet know all the applications that will emerge from this area, so it is difficult to give definitive answers, but we think that dialogue as these emerge, ensuring that we understand how opinions are being formed and can help inform opinion-making, is the critical thing.

Q236 **Chair:** Would you say that we do not yet have a real sense of the overall societal impact of this technology?

Professor Walmsley: I echo what Winni said. When you build a transformative technology like this, you can expect it to transform society, so we have to be prepared for that. We do not know all the areas it will impact. Who knew in 2002, when Facebook came in, that it would have such a dramatic effect on our society? That is the kind of thing we have to be aware of and open to, and continue to explore and have dialogue about.

Q237 **Stephen Metcalfe:** We are beginning to talk about machine learning and artificial intelligence against an ethical framework. Assuming that it is going to have the same sort of impact as Facebook, do you think that those working in the area treat that with enough seriousness? Is it a serious issue for them, or is it a tick-box exercise at this stage?

Professor Walmsley: 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.

Professor Hensinger: One of the societal impacts that people often do not recognise is the fact that quantum computing, like nothing else, has a very strong impact on getting children into STEM subjects. We put a walk-in quantum computer installation in the middle of London a year ago. 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. A sixth-grader convinced his parents to fly all the way from America to visit me. It was a most humbling experience. A primary school kid came to our installation and refused to leave until the father promised he would give that kid a university textbook on optics, which is one of the technologies we are using in our programme.



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There are tremendous societal impacts, with things like AI changing the world and maybe the creation of new pharmaceuticals, but right now, unlike anything I have seen, people are realising what we are doing. We are putting an atom in two different places; we are doing a computation in parallel universes, and that drives tremendous enthusiasm.

Q238 **Chair:** Presumably, there are risks as well as opportunities.

Professor Hensinger: There are always risks with any technology. As you know, conventional computers brought a tremendous number of risks, but they also brought a tremendous number of opportunities. As a country, we need full understanding of the opportunities and the risks, and we need to be able to do that by engaging closely with the technology as appropriate, and regulating it as required.

Q239 **Neil O'Brien:** This question is about focus versus breadth. Should the next phase of the national quantum technologies programme focus on the things the UK is strong in, or should it be more broadly based? To sharpen the question a little bit, obviously we have more limited resources than, say, the Chinese state or the US security services. Are there things that we should not be doing because they are being done better elsewhere in the world? If we are going to focus, there have to be some things we are not doing. Are there particular things we should focus on, or are we at a stage when we should be generally scattering bread on the water because we do not know what we will be strong in, or what is going to be fruitful?

Professor Walmsley: I am happy to say a few words about computing in that context. At the moment, we believe that the UK platform is a leading contender for a scalable platform. It is different from those that are being pursued by some of the IT majors, but it is still too early to tell. We can see challenges to those other architectures. Therefore, what we have designed into our programme is what we call core technologies, where the UK has the capacity and capability and is in a leading position, and there are no science barriers to building those into functioning machines.

A second set of emerging technologies are areas where there are still a few science questions to answer, but, if those are overcome, they become viable alternatives. We think that is a reasonable way to spread bets and make sure that, whatever transpires in the next decade, the UK remains in a leading position and has expertise and skills, and the technology base to exploit them.

Professor Bongs: The phase one programme has already focused on areas in which the UK is world-leading. That has been a very good strategy, because it has allowed us to build on that world-leading position and create a programme of which the world is envious. At the last European flagship meeting, sensors were held up as a shining example of how things should be done. At the moment, companies approach us and say, "We are going to the UK. We want to invest in the UK. This is our



prime area of interest in quantum technologies because we know the UK is world-leading.”

Q240 **Neil O'Brien:** You think it is already quite focused and you are happy with the level of focus. You do not think it should be tightened further on the things we are genuinely leading.

Professor Bongs: I do not think tightening would be a benefit, because we have four very diverse hubs that all complement each another. There is a large synergy in the industry supply chain. It gives industry something like a phased entry to nearer-term quantum technologies, to learn how to build the technologies and the nuts and bolts of the supply chain, and then build it up gradually for quantum computing in the long run. For instance, we also need trapped ions and the basic building blocks of some of the quantum computers in the sensing areas. There are very good synergies in the supply chain between different hubs, which then build the economic ecosystem to drive that forward and sustain it over the longer term.

Professor Walmsley: That is a really crucial point. If our objective is to build a quantum technology industry sector in which the UK has a leading role, there is a critical mass argument. If you under-invest and do not build critical mass, you simply will not have a successful ecosystem.

Kai has already talked to the supply chain and SME involvement. Another unique feature of the UK programme is investment in high-level skills through the skills hubs. That is something that other programmes have not yet sought to replicate, and it provides a capability for the UK in the future that will be crucial for the success of this new sector.

Professor Hensinger: I agree with all that has been said. One thing I would like to add, starting with what Ian said, is that one of the threats to quantum technology in the UK is skill shortage. We have these fantastic skills hubs, but we do not have quite enough training for PhD students. That is something we need to be aware of and start working on now, because the industry is starting to become far more active and will need the right people in the sector.

Q241 **Vicky Ford:** Maybe because of the way our questions are worded, they do not seem to differentiate much between quantum technology and quantum computing. I have seen a range of different uses of quantum—quantum sensors and quantum clocks—and at the Royal Society there is quantum technology in the form of brain-imaging sensors. It is really important that you make clear to us quantum computing—super-fast processing and problem solving—versus other quantum technologies so that we have clear language on that. I am not sure I have got that from what we have been listening to so far.

Chair: Does anyone want to comment?

Professor Hensinger: I would like to comment on that and extend an invitation to the Committee, if there is time, at some stage to come to



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the University of Sussex. We have a very broad range of quantum technologies. We are part of two quantum technology hubs. We engage in ghost-imaging, looking round corners; we use magnetic field quantum sensors to look at the brain; we are working on a quantum internet; and we are building a quantum computer prototype. This might be a very nice opportunity for you to see that.

Chair: Thank you for that; we appreciate the invitation. Vicky, do you want to come to your questions?

Q242 **Vicky Ford:** I will come to my questions, but perhaps you can be very focused on areas other than just quantum computing. How closely do you think the proposed set of innovation centres should match the existing structure of the four hubs and their areas of focus?

Professor Bongs: I will give a general answer that might be applicable to both. We should not be too prescriptive as to exactly where the innovation hubs are located and what they look like, to allow a flexible approach to whatever is most appropriate in the different sectors, be it quantum computing, sensing, communications or imaging. What is very, very important is that they enable smooth links between the academic-funded programme of the quantum hubs and the industry side, with the challenges, 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, to make sure that we harness all the things that have been developed in phase one and pull that through quickly to full economic benefit.

Q243 **Chair:** Do you support the principle of the innovation centre being alongside the hub?

Professor Bongs: A lot of developments have happened in the hubs, and they should definitely pull all that through. There is a big potential to be harnessed, but they should also be open to pulling things through that have happened in the wider landscape.

Q244 **Vicky Ford:** The four hubs are computing, sensing, imaging and communications. Are those still the right four categories—yes or no?

Professor Bongs: Yes.

Professor Walmsley: Yes.

Professor Hensinger: Yes.

Q245 **Vicky Ford:** Good. And those are the right areas to continue to focus on. Is there a danger that, if you put the innovation centres in a different location from the hubs, you could end up having a disjoint between the research end and the commercialisation end? Do they need to be in the same geographic location, or are there advantages to the innovation centres being spread around?



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Professor Bongs: There is a certain risk, but you could have innovation centres spread across different locations. My view is that there are ways to mediate the risk. We have had very good experience with co-location—for instance, at NPL or in Chelmsford.

Q246 **Vicky Ford:** I have a vested interest in that, which I have declared already: one of the companies is e2v, based in Chelmsford. Anyway, there are ways to mitigate the risk. Any other thoughts on that?

Professor Walmsley: One should not think of these innovation centres as one size fits all. Some of them may be better co-located, because they are on small-scale, short-term, immediate applications and that sort of activity. Others, particularly in computing, where it is long term and you need a large-scale, moon-shot kind of approach, should be considered in a different way.

Q247 **Vicky Ford:** What is a moon shot?

Professor Walmsley: An Apollo-like programme, where there is a very concentrated effort with a very singular objective: the UK should build a quantum computer. That is the kind of thing I mean.

In all cases, the hubs, and the technology drive that is coming from them, need to be interactive with the innovation centres, but the character of the innovation centres and the specific location could be quite different across the piece.

Chair: There needs to be flexibility in design.

Q248 **Vicky Ford:** Is there enough time to build these innovation centres, given that the first phase of the technologies programme is coming to an end next year? Is there a timing issue?

Professor Walmsley: The first critical thing is skills; we have talked about skills in technology development. If we do not have continuation of the hubs, those skilled individuals will go elsewhere in the world, and we will have dissipated our advantage and our resources. The innovation centres ought to move rapidly. I don't think the timing is as critical as for the hubs, but we need to be getting that on the agenda.

Q249 **Vicky Ford:** When do you need a decision on the hubs?

Professor Walmsley: We need a decision on the hub funding within the next two months.

Q250 **Chair:** We are looking towards the Budget in the autumn, but you think it is that time-critical.

Professor Walmsley: I will tell you what the timing is. The current hubs end at the end of December 2019, so we expect that people will want to understand what their trajectory is between six and nine months before that, which puts us at March, April or May next year. Therefore, we need to be clear what the hubs are going to be and what the funding is going



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to be well before that time, so that people have some certainty. That means that, by March next year, this needs to be completely sorted.

Q251 **Vicky Ford:** Do you all think it is a decision that needs to be taken in the autumn?

Professor Walmsley: Yes.

Professor Hensinger: Definitely.

Vicky Ford: It might be worth our getting a slightly faster letter out on something like that, if you thought that was useful, Chair.

Chair: I do. Thank you very much.

Q252 **Vicky Ford:** I am sure you will say yes to this, but are quantum computers close enough to market to merit that space programme-type concentrated approach in an innovation centre?

Professor Walmsley: In my view, the trajectory for them is that there will not be a saleable, fully scalable, fully functional digital quantum computer that is entirely fault-tolerant on the market within the next 10 years, despite what IBM and Google may tell you. That does not mean it should not be done, because of the level of transformation that will happen when it does. Along the way, there are applications for the small-scale processes that are already emerging, which I think will begin to build the market. If you look at the IBM model, that is exactly the way they are approaching it.

Q253 **Graham Stringer:** We have talked about this country being a world leader, but some of the major companies are not investing here. Bosch, Google and Intel are investing elsewhere. Why is that?

Professor Walmsley: IBM, Google and Microsoft are the companies that have made big investments in quantum computing technologies. They have chosen the superconducting technology, and there are a number of historical reasons for that. I do not know for sure, so I am speculating to some degree.

IBM has traditionally had a very strong regular superconducting electronic group, and has taken advantage of that to build its quantum device. Google did what Google does: it hired a group that was one of the world leaders in that technology. Microsoft has taken a very different approach, which I think is quite high-risk, and is a technology that nobody else in the world is pursuing.

Because they have made their bets, they are not so easily swayed to take on a rival technology platform. Nevertheless, for the UK, that is an opportunity: first, we have great strength, as Winni said, in the core technology we are pursuing; and, secondly, we have key capabilities in that superconducting technology such that we can provide leverage to whatever comes out of those areas.

Q254 **Neil O'Brien:** What is the high-risk technology that you mentioned



Google is pursuing?

Professor Walmsley: The approach it wishes to pursue is called topological quantum computing. The advantage of it is that you rely much less on error correction, which is a core part of the technology that we are developing in the UK. Nevertheless, the hardware that you need for that—the physical qubits—has not yet been demonstrated, so there is a much further distance to go.

Q255 **Graham Stringer:** Should the current governance structure, the strategic advisory board, continue, or should there be a different governance structure? If so, what?

Professor Walmsley: The structure, given where we started, has worked reasonably well. It could certainly be helpful if there was an increasingly improved way of joining up the different parts of the activity, in particular working across EPSRC and Innovate UK. It has been transformed, but there is still some way to go. If innovation centres are in there, having a body that has a bit more executive power to co-ordinate across those things would be quite helpful.

Q256 **Chair:** Do you all agree on that?

Professor Hensinger: It is a sensible thing. It is important to have that body close to the actual research. It should be an executive that somehow takes a step back from the active research, so that there is no conflict of interest. I absolutely agree on that.

Q257 **Graham Stringer:** Have we anything to learn from the way the United States does it, with DARPA, its structure? Should we follow that?

Professor Walmsley: What can we learn from DARPA? It is a very actively managed programme. It is at scale, and it deals with specific sorts of deliverables. There are some advantages to that approach, but you have to see it in the context of the US funding ecosystem.

The strengths of the UK have been that successive Governments have consistently put science and technology as a priority, and that consistency has been really important. Picking particular programmes, putting money in and then withdrawing it later is not the way to deliver a programme of this scale.

Q258 **Graham Stringer:** Earlier, you mentioned the strengths we have in SMEs. In a lot of sectors, clustering SMEs seems to work very well, but the SMEs in this sector do not seem to be clustered. Can anything be done about that?

Professor Bongs: There is definitely some clustering around the hubs, providing focal points for industry to interact with. That was very helpful in the last phase. We have seen different SMEs cluster around the hubs, at least in the interactions, and in the network around them, so that there is an emerging ecosystem where people build one component, others make the next component, and others put them together in a



system and then apply the system. Those clusters are building around focal points, which can be local, or via certain hubs or innovation centres.

Professor Hensinger: One of the ideas is for these innovation centres to provide a co-locating space, with the ability for SMEs to work closely with researchers. Going back to a previous question about innovation centres, the hubs are not just based at one university; they are decentralised among many universities, so the innovation centres should somehow mirror that. Most importantly, they should be driven by industry; they should not be an academic exercise.

Coming to what you asked, it is very important for innovation centres to have clustering of SMEs and bigger companies to form an ecosystem. That should be driven by industry.

Q259 **Graham Stringer:** This country is very good at new ideas, but it often does not patent things as well as it could, which leads to other businesses and countries exploiting them. In the area of quantum computers, what percentage of patents are held in this country?

Professor Walmsley: That is a good question, and I do not know the answer—the specific number.

Graham Stringer: Is it easy to access? Could you write to us? Does anybody know?

Professor Walmsley: We can certainly find something on that.

Q260 **Graham Stringer:** That would be really helpful.

Professor Hensinger, can you tell us what the supply chain initiative is and what it entails?

Professor Hensinger: We have taken a few steps at the University of Sussex to produce a supply chain. One of the steps was a bid to the European regional development fund. This is an opportunity, but it has not been decided yet.

In the bid, we made a case for qualified quantum engineers to help start-ups and SMEs to engage with researchers towards prototyping, allowing for financing to give SMEs the opportunity to engage in those activities. With the limited budgets they have, they often simply cannot afford to engage. We are trying to get ready and take first steps towards an innovation centre, which is critical.

We also work in Brighton with the Brighton digital catapult, helping SMEs in particular to understand the opportunities in quantum computing—for example, thinking about quantum software development and engaging in the emerging quantum computing sector.

Q261 **Stephen Metcalfe:** We have already mentioned skills quite a lot today. In the submissions we have received, we are told that there is a skills shortage. Can you say how severe that shortage is, if you agree there is



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one, and what you think is the best way of filling it?

Professor Walmsley: I mentioned skills earlier in the context of skills hubs. They are producing the very high-level researcher skills that I think are critical for driving this.

One of the features that we are now beginning to see in the hubs is difficulty in getting the skilled engineers who are needed to take the technology out of the laboratory and build the next stage. Conventional engineering skills are extremely high-level in the sense of being bachelor or masters level but, nevertheless, not research level. Those are the kinds of skills we will need to have. It is likely that high-level technical and technician skills will also be needed. Those are not properly catered for in the current programme, but there are opportunities to do that, by partnering with the skills agency, FE colleges and so on.

Q262 **Stephen Metcalfe:** You think that extending the existing programmes can fill the gap, rather than something more radical.

Professor Walmsley: I think new partners need to be brought in to help with that skills gap, but we should not neglect maintaining the current activity. We need new additional partners.

Professor Bongs: I agree with everything Ian said. There is a large appetite for transferring skills quickly to industry in existing frameworks. We have good experiences with secondment programmes between us and Teledyne 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.

Q263 **Chair:** You are seeing an appetite from companies.

Professor Bongs: Yes. We have been oversubscribed. We have a masters course on translational quantum technology, and we have more companies wanting students than students in the programme wanting go to companies for six months.

Professor Hensinger: We have a tremendous shortage. In addition to what Kai and Ian said, we train too few PhD students. That is quite obvious. We can see that is the case because, when we advertise for staff positions, we get a lot of applicants from overseas; we have to take applicants from overseas, even from Thailand and from America, because we simply do not have enough trained PhD students in the sector.

Besides PhD students, we need other transferable skills—engineers, for example. Some of the PhD students we are taking on right now are engineers. This is very much a grey area between engineering and physics, and it is becoming more engineering than physics.

Chair: That will please Stephen.



Q264 **Neil O'Brien:** Have recent Government announcements on more PhDs over the last two years made any difference to you, or not enough difference to fill the gap in demand for PhDs in your space?

Professor Hensinger: There has been a very good start. As Ian pointed out, the quantum skills hubs have been very successful, but the number of PhD students in the system is by no means sufficient in quantum technologies.

Stephen Metcalfe: That was going to be my final question.

Neil O'Brien: Apologies.

Stephen Metcalfe: I think we have covered everything. I just want to clarify that industry is playing its part in bridging its own skills gap. It knows that it has to do more.

Q265 **Carol Monaghan:** Apologies for my lateness this morning. Could I keep with the point about skills? You mentioned engineers in particular. Is an issue that we are not training the right types of engineers? I am thinking in particular about courses in optical engineering, for example. Are universities looking at tying in with the needs of industry?

Professor Hensinger: It is emerging. At Sussex, we have a brand-new masters programme in quantum technologies, but we have to get much better. The second phase of the programme will focus further on training in those skills, especially in the engineering sector, as you say.

Professor Walmsley: I concur with that.

Professor Bongs: We should look not only at engineers, but at highly skilled technicians. There is more need to provide new training in that area.

Q266 **Carol Monaghan:** In some evidence that has come to us, we have had submissions about the US International Traffic in Arms Regulations and dual-use technology. Is the quantum community sufficiently aware of those regulations? Are hubs the right places to ensure that academics are not falling foul of the regulations?

Professor Walmsley: Sufficiently aware? I don't know. Are we aware and are we trying to raise awareness? Absolutely. We have had visits from several Government Departments to help inform us about some of those issues.

When we develop the hardware, and indeed the software, as far as it is patentable, in the hubs, we are clear about what we are doing there and why we are doing it. When we partner and work with our US colleagues, we try to be clear about which bits of their know-how we are using and where it may be incorporated, or not, in the system. It is very much on our radar screen, although we could no doubt continue to do more.

Q267 **Carol Monaghan:** Are those regulations in danger of dampening



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innovation in the hubs, because people are concerned about how the particular technology is developing?

Professor Walmsley: People are aware enough to ask the questions before they enter collaborations, to make sure that they are not bringing in background IP or knowledge that may end up being a challenge later on. There is more caution in the hubs about global partnerships than there has been in, say, a pure research programme. I don't think it has yet dampened things, but there is caution about it.

Q268 **Carol Monaghan:** The other two witnesses are nodding, so I take it that you are in agreement with Professor Walmsley.

What support do the hubs offer academics who are not involved in the national quantum technologies programme, particularly in terms of those regulations?

Professor Bongs: The training programmes we have received have been open, so that anyone who is interested can come in. If we talk to people about joining in with collaborative work with the hubs, we make them aware.

One issue with the regulations is that they have very personal consequences. Any lawyer will advise a different party: one organisation advising a different one legally is not trivial. You can only raise awareness and make people inform themselves and make their own decisions, to some extent.

Professor Walmsley: In NQIT, we produced a short, one-page summary of things to be aware of, which we give out to people who join the programme. We have also done sessions on these matters in our project forum and skills hubs, which we make available to the wider community.

Q269 **Carol Monaghan:** It is freely available to them.

Professor Walmsley: It is available. I do not think we have put it on our website, but it is something we discuss with collaborators and people at these events.

Q270 **Vicky Ford:** I want to try to get a clearer answer on the innovation centres versus the hubs. Time and time again in this country, we have seen research leading to brilliant ideas, but then the manufacturing happens in other parts of the world. You are all on the academic side of the research. I declare an interest in having a constituency where there is work on the manufacturing side.

I am happy for you to say no, but is it important that some of these innovation centres go towards where we have areas of manufacturing expertise, as well as having some of that manufacturing building round the existing hubs? That is an argument that has been made to me. Is it a fair argument? I think you said you can manage the risk, but clearly there is a risk. What happens is what has happened again and again,



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which is that we have the bright ideas here, but it gets manufactured somewhere else.

Professor Bongs: There is definitely a case for that. The most important thing is to create a construction to get a smooth transition, so both parties, from the academic and the industry sides, need to be involved in the governance of innovation centres. You are always going to think about bi-locations or several locations for them. One innovation centre has two locations to bring in the respective expertise at the location that is most useful. Intrinsic joint governance is quite important, to make sure that we get the transition right. I do not mind if that happens when the innovation centre is sitting at one of our industry partners, if we get the manufacturing right.

Professor Walmsley: I broadly concur with that, but I revert to the notion that not all innovation centres should be the same. I think they will be quite sub-field dependent.

To take computing, as that is what we have thought about most in NQIT, the landscape we think will be crucial to developing that ecosystem is, first, the hubs—the research that pushes the technology performance based on new understanding in science; and, secondly, the new companies and existing companies that are emerging. One thing we have not really talked about is the great interest among students, researchers and venture capitalists for start-ups. We are seeing lots of those coming out of the system now. Those are the key areas where new technology and new engineering will be done, and they are outside the realm of existing companies, because existing companies do not have the appetite or the capabilities.

Q271 **Vicky Ford:** I want to hear you say that these are going to be areas where new technology, new engineering and new manufacturing are done. Are we doing enough for the manufacturing to stay here?

Professor Walmsley: That is exactly the point I was getting to. How do those 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. You can understand how that ecosystem might then work to do exactly what you say as regards engineering and manufacturing.

Professor Hensinger: I agree with everything that has been said. At Sussex, we are in the process of spinning out a company to build quantum computers, to manufacture them. It is absolutely core to our mission to do that in conjunction with the innovation centres and to do it in the UK.

Professor Bongs: I have one comment about ensuring that the manufacturing is done in the UK. An important point is that, in the overall



ecosystem, we are trying to create an industry, so that people doing services based in the sensors area—for instance, using sensors to create services such as underground surveying or clinical services such as brain diagnosis—are heavily involved and interlinked with the manufacturers. If we have both of them in the UK, it essentially creates a sticky point, so the manufacturer has the advantage of knowing exactly what the user needs.

Q272 Chair: We have a clear impression that this country has got into a good position with investment in the national programme. Is there any final clear message that you want to give to us about the most important thing that needs to happen to ensure that we maintain our advantage?

Professor Walmsley: I think we have covered most of them. One is to build on the current success. There is the immediate need, which we have discussed, around continuation of the hubs. Then, there is enhancing the manufacturing and engineering capacity through innovation centres of a variety of kinds, and supporting that programme with the skills needed to do that, not only at the PhD level—although that is crucial—but further down.

Chair: Any final comments?

Professor Hensinger: The key thing is that it is absolutely critical that there is no break in the programme. We cannot afford to lose the skills we have amassed here in the UK.

When the first iteration of the programme started five years ago, we were truly in the lead. Nobody else was engaging much in the sector. China has just announced a \$10 billion investment in the sector, and other countries, including the United States and Germany, are following suit. It is really important to capitalise on what we have done and ensure that we can stay as strong, and grow stronger.

Q273 Chair: Maintenance of the funding for phase 2 this autumn is critical.

Professor Hensinger: Absolutely.

Professor Walmsley: Absolutely.

Professor Bongs: Absolutely.

Chair: Thank you all very much.

Examination of witnesses

Witnesses: Professor Cross, Dr Bentall, Dr Shields and Dr Thompson.

Q274 Chair: Welcome, all of you. Would you introduce yourselves, please?

Dr Thompson: I am Peter Thompson, the chief executive of the National Physical Laboratory. We were set up by the Royal Society over 100 years ago to support trade. We are part of an international community of



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national measurement institutes that maintain the international system of measurement, which we use to support the development of standards. You need to be able to understand how to measure in order to adhere to standards. We provide test and evaluation to support industry to get its products to market. To do that, we also develop our own technologies.

Chair: We need to keep it tight because we have a lot to get through. Thank you very much.

Dr Shields: I am Andrew Shields. I lead research in quantum technologies in Toshiba. I am assistant managing director of the Cambridge research laboratory of Toshiba. I also chair a standards group in ETSI, which is producing the first standards for quantum key distribution technology.

Professor Cross: My name is Trevor Cross. I am chief technology officer at Teledyne e2v. I also head our quantum programme, which numbers about 33 people. Our company specialises in high-tech, low-volume specialist technology, and the quantum area is something we have been looking at for about six years. I was involved at the outset in the Birmingham hub proposal and helped shape that. I think this is a terrific area.

Dr Bentall: My name is Dr Mark Bentall. I am the head of technology, development and innovation at Airbus Defence and Space.

Q275 **Chair:** Thank you all very much for attending. There are four of you on the panel, and we have a lot of questions to get through. Please keep your answers succinct and do not feel you have to answer everything, if that is possible.

First of all, how important are quantum technologies compared with other emerging technologies, and what priority should Government give them?

Professor Cross: This is a terrific underpinning technology that will affect masses of the ways we do things today. If I can draw a parallel, 30 years ago in the world of imaging and televisions, the object in my left hand was the sensor in a TV camera and the cameras were the size of refrigerators. Who would have thought 30 years ago that the sensor has turned into something like the one I have in my right hand?

Chair: What else do you have in your pocket?

Professor Cross: I have a lot of pockets. More than anything, a 2mm square device in my phone catches full motion video and can send it around the world in a matter of seconds. I challenge anybody to say that we can envisage what quantum technologies can do. Already, in our laboratories, things that are this shape are the first embodiment of things that can do a job that people want done using quantum technologies. We can see a road map where they can turn into things like this. It is a long journey, but we are at the point where these things are becoming



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useable out in the field to do jobs that cannot be done today. That is why it is so exciting. The market is starting to emerge, but the sky's the limit.

Q276 **Chair:** The answer to the question is that the Government should be giving this considerable priority.

Professor Cross: Absolutely. Thank you for translating.

Q277 **Chair:** Are there any other answers, quickly?

Dr Bentall: From where we are in Airbus, we see it as a fundamentally important technology. Again, it is an elementary technology that spreads to many different areas. The key thing is that we see the limitations of current technologies. We are in the digital world and we are still exploiting digital technologies today, but we also see where there is a natural limitation to those technologies. Quantum technologies are a fundamental key to unlock that potential and where we can go.

Q278 **Chair:** What are the main potential societal benefits and challenges that we face? What are your organisations doing to address the challenges or threats that might exist from this technology?

Dr Thompson: The benefits span the big challenges that have been identified recently by the industrial strategy: future mobility, healthy ageing, AI in data and clean growth. Quantum technologies can impact on all four of those.

Challenges? One is public understanding. There has been some excellent work that has been undertaken in that space. Another is trust, which comes from proper testing and verification of the technologies as they are developed.

Q279 **Chair:** Any other thoughts about challenges we face?

Professor Cross: The industrial players can see ways to solve the technology problems, but unlocking the true value in the economy is not just about the technology. It is about what we encourage people to do with it. For example, sensors that can see through the ground with a precision that you cannot have today would be terrific at identifying sink holes before they happen, or where buried utilities are in the ground; or where weaknesses are in the ground when you are building major infrastructure such as High Speed 2.

A technology push will not do it on its own. We need inducements and encouragement through things like big demonstrator programmes, and potentially help in the regulatory framework, to say, "You should use new technologies." Once people sample it, they will start to realise that it saves money and makes projects quicker. It takes uncertainty out of the schedule for big building projects. It is not just about technology and product.

Q280 **Chair:** Dr Bentall, in your written evidence you outlined the potential of quantum sensors in detecting submarines underwater. Does it pose a



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threat to the UK's nuclear deterrent if they can be identified from above?

Dr Bentall: Yes, it clearly would from whoever has that 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.

Q281 **Chair:** Can it be overcome, and in what timescale?

Dr Bentall: At the moment it is not something I have a timescale against, but it is a potential in the future of what quantum technologies can bring.

Q282 **Neil O'Brien:** How can the next phase of the national programme help to close the gap between primary research and commercialisation? That is a thing we are always concerned about being bad at in the UK.

Dr Bentall: With the current programme, we see a 90:10 split, 90% being focused on the academic side and 10% focused towards the industrial side. A large part of the industrial side, from where I am in large industry, is mainly focused towards small to medium enterprises. Academia is very broad in investment; then SMEs take that into quantum-based solutions. From a system integrator point of view, our focus is quite narrowly on our market. Therefore, access to that has not been as successful as we would have wished.

We have been supporting innovation centres to improve the pull from industry, to get the know-how transfer from the academic and SME community into larger industry. We have a huge number of engineers who do not know or understand the potential of quantum technology. That needs to be addressed and it needs to be done relatively locally to where our engineering resources and capabilities are based, so we see the benefit of the innovation centres.

Q283 **Neil O'Brien:** The geography is crucial.

Dr Bentall: Yes, for us; for exploitation, it is crucial to where that education happens. We find that people leaving academia in the first phase are critical to where the capability remains.

Dr Shields: It is not just the geography. We also need much better integration of the R&D programme between industry and academia. In phase one, we really had two programmes: the EPSRC 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. We need a much better integrated programme, which integrates academia, industry and Government partners.



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Professor Cross: I totally agree with that. Right from the outset of the first hub programme we identified that it would be a really good idea to have industrial players inside the hubs, and we tried to do that. The funding mechanism did not allow that to be supported at scale, so we found a way around it, but it was suboptimal.

Q284 **Neil O'Brien:** Out of interest, how did we manage to get that wrong? How did we get different timescales for the EPSRC programme and Innovate? How did we not have a conversation where they were lined up?

Dr Thompson: First of all, we should celebrate the success of the first phase of the programme.

Neil O'Brien: I am not doing it down.

Dr Thompson: Those were the two entities that were able to deliver the funding to rapidly set up that programme four years ago. We must maintain the pipeline through the quantum technology hubs, but, moving forward, there is an opportunity to take a more top-down view as to greater agility on where the money is spent to drive it through the sectors.

Q285 **Neil O'Brien:** Do we anticipate, if there is a further phase, that the same 90:10 split would be roughly the right Innovate versus EPSRC split in funding?

Professor Cross: We should be talking about 60% industry-led. That does not mean that it will be spent in industry. We are talking about directing it to the areas that have the maximum commercial potential. We absolutely need an underpinning continuing science programme that has blue-sky freedom associated with it, but, from the outset, this investment was supposed to be about innovation for wealth creation as well as other public goods. That is fair and legitimate, but we might have to change the rules around how academic players are measured if they take funding from that particular source. That is only fair. People behave according to how they are going to be measured.

The UKRI construct is a terrific opportunity. We have all the silos of the current research councils. We do not necessarily need to top them up with additional funds. You could do it in a cross-cutting way, and the quantum programme is a really good example of how to do that.

It is going to be absolutely critical to set up the governance of the future programme in a different way, with executive powers, a very strong industrial advisory board and an academic advisory board. But make the decisions about the priority of where the funding is allocated in a well-informed, fair, open and transparent way. That could serve the objectives of what I understand UKRI to be about.

Q286 **Neil O'Brien:** That is extremely interesting. It is quite a different model. Do you detect interest from UKRI to do that, to break with the



usual silo?

Professor Cross: Absolutely. Some of us here were part of helping to prepare the Blackett review. Recommendation 11 is all about that. I really hope that we can deliver on the aspirations, because that will serve better the anchoring of continuing wealth generation in this country. We can seize a larger market share as some of this technology transitions to the new way of doing things.

Q287 **Neil O'Brien:** Professor Cross, you have warned against the innovation centres becoming just extensions of the current hubs. Could you spell out exactly what your fear is about that?

Professor Cross: I would not say fear. It is all about how we can best use the resources we might get. There is a terrific advantage in having innovation, thinking, capability and space in the universities, but we should also recognise that, in turning the science into products and services from which we can make money, a huge amount of IP as well as manufacturing capability will come out of the industrial base.

A lot of industries, and sometimes that includes SMEs 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.

Q288 **Neil O'Brien:** What does not just making them extensions of the current hubs mean? What does that require the innovation centres to be, in your view?

Professor Cross: Above all, you need co-location of people. That does not mean they have to be at the university. Even in the existing phase of the programme, we have had a number of programmes where we physically co-located. I have an office in Birmingham University. When we put people into that office, as part of teams, things work really well. We are building a satellite in our facility, and it is pretty much split down the middle in terms of the human resources.

With the National Physical Laboratory, we have another collaboration, on miniaturising atomic clocks. When people from NPL come into my factory, or my guys go to NPL, it does not really feel like they come from anywhere else. They are one team, and that is what we have to build on. I want innovation centres to go large on that, with bigger budgets and really hard challenges, to actually produce capabilities that customers such as Airbus want. Airbus, Thales and all the big companies such as Leonardo say the same thing: "Give me a prototype I can look at. Show me the functional advantages of what you are saying in the science programmes."

In the next 18 months, we are going to see a number of out-there-in-the-world real demonstrations of some of those capabilities. That will be a step function increase in the major industries becoming involved. The innovation centres play a key role in that. They are in a kind of neutral



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territory, which might be adjacent to an industrial facility or it might be at Harwell or at NPL; it might be at a university, but inevitably—

Q289 **Chair:** How many innovation centres do you think we need?

Professor Cross: The four key strands in the hubs have an enduring logic. It is not a bad idea to think that you need something in each of those spaces. Will it be one-to-one mapping? No. There might be two in centres or there might be one in space, for example. It might not be 100% alignment with the hubs, but there will be a visible logic that connects them together around what the applications demand and where the commercial potential is.

Q290 **Chair:** Do you agree that there needs to be quite a lot of flexibility about how they are designed? It is not a one-size-fits-all model.

Professor Cross: Yes. I think it would be a mistake to be too prescriptive in the brief. I would say, "Here is the opportunity. Here is what we are looking for in terms of outcomes. Go away and give us some proposals to deliver those outcomes." You will find that industries and universities collaborate in those proposals.

Dr Thompson: In some respects, even the phrase "innovation centres" has painted a picture in people's minds. This is about accelerating the technologies from the hubs and elsewhere into commercial applications. Industry is absolutely critical, and engaging with industry in the design of those and what works for them, and then getting their investment, is the key outcome from the innovation centres debate.

Q291 **Vicky Ford:** How close are each of you to actually generating any revenue from this, or using a quantum technology-enabled component in something that you are trialling, testing or practising on?

Dr Thompson: We deliver time to the City, disseminated through a fibre for high-frequency algorithmic trading. That is done as a commercial service.

Q292 **Vicky Ford:** You are making money out of it today.

Dr Thompson: I would not say that we are making money, but we are recovering costs.

Q293 **Vicky Ford:** You are generating revenues.

Dr Thompson: Yes.

Dr Shields: Hopefully, we are not too far from generating revenue from quantum technologies. We have built a prototype for secure communications. We have been trialling that with BT and various customers of BT, and found some interest in it.

Professor Cross: Today, we have taken orders for delivering some components for cold atom trapping to the university science base. That is always a good start. It is a real milestone for my finance director. During



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the end of this calendar year, we will be sampling miniaturised atom clocks for industrial users. I now have people quite literally banging on the door and saying, "We would like to buy one of those." We are not quite ready to say that it is roadworthy.

Q294 Chair: Do you have one of those in your pocket?

Professor Cross: The objective is to be able to do just that, but today I don't have one in my pocket.

Dr Bentall: We phase our research, and this is still in what we call blue skies, which is the very first part of our research phase, but we have a programme running on quantum key distribution over UAVs. We are also trialling some quantum technologies for navigation-less infrastructure navigation systems.

Q295 Vicky Ford: In the US, they have the DARPA structure, which helps to focus defence spending into transformational research, as I understand it. Should we be using that sort of strategy in the UK? Professor Cross, you mentioned that in your submission.

Professor Cross: The DARPA scheme has a lot to recommend it. We cannot of course separate it from the funding levels that are available over there. Actually, I think we can be smarter than that, but setting the challenge and potentially having competing early stages of programmes and then selecting the winner, which might be a bit painful, will probably lead to a faster rate of progress.

Q296 Vicky Ford: It is setting the challenge style.

Professor Cross: Yes, and I think we have seen the beginning of that with the current Innovate UK pioneer challenge in quantum technologies in the current funding round, which is a £20 million opportunity. A number of bids have gone in against that. They are very challenge-focused. They have pulled together miniature supply chains in those bids, and I think people will respond to that.

Q297 Vicky Ford: Are there any particular challenges that you, as a panel, think we should be encouraging the Government to support?

Dr Thompson: There are a number of examples we could consider, such as demonstrators of non-reliance on GPS, through precise timing and quantum sensors.

Q298 Vicky Ford: We may not need a Galileo instead.

Dr Thompson: That is quite possible.

Q299 Chair: What is the likely timescale for that?

Dr Thompson: To do a demonstrator of that nature? Probably in the order of three years or something like that. But that in itself brings together not just quantum expertise but all the engineering expertise and



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the supply chain. It raises the public profile of what we can do and gets products out there and developed more rapidly.

Q300 **Vicky Ford:** Are there any other grand challenges?

Dr Shields: I would suggest integrating quantum cryptography in communication systems to make secure communication systems with everlasting security, and integrating with conventional technology and developing the standards and certification processes that we need for that technology.

Professor Cross: Putting things into space. You might think that is a bit odd and a bit niche, but actually it is a massive technology driver. The chief technology officer of Shell is on record as saying that they used gravitational measurements from space to augment their dataset in looking for new oil reserves. That is with the current technology.

The cold atom technology from Kai's hub, and some things we are working on, could improve the resolution of those measurements by maybe one or two orders of magnitude in time. That would be transformational in looking at, let us say, the water table variation under the ground, looking at flood and drought prediction. Water is going to become a really critical resource. You could even imagine in the fullness of time having an always-on system looking down at Earth.

More than that, the technologies that you develop and miniaturise, and reducing power requirements for that, will become much more available for handheld instrumentation, maybe even for the construction industry to look through the floor, on an affordable and much more ubiquitous application. It could really change the economics of building. There are estimates of savings of 1% or 2% in big infrastructure projects if you know what is coming and you do not experience big delays. Space and construction would be my two.

Dr Bentall: The good thing is that those three work for me. On top of that, in the computation space, we see large potential for simulation to improve our productivity. If we can do one on simulation—something like computational fluid dynamics—we can significantly reduce things like wind tunnel testing, which are very costly and very timely. There is potential for a new products model. A simulation one would be very beneficial too.

Q301 **Neil O'Brien:** Dr Thompson, can you tell us a bit about the programme you are leading to engage large industrial firms in this space? Are you managing to engage firms that are not already heavily engaged in this space? Have you done anything like this before?

Dr Thompson: Yes to the first question. I will say a little bit about what we have done. We were tasked by UK Research and Innovation and we have been engaging primarily with major industries in the UK, not just the major industries that are already investing in quantum technologies, represented here, but companies across many different sectors that we



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believe would and could engage and pick up on some of the quantum technologies.

We have held a number of meetings with people from across many sectors just to understand what, why and when they would invest in disruptive technologies, in particular quantum. We have then done very specific sector events: health and life sciences, financial services, and defence, aerospace and space, as well as working with other activities that the hubs and other organisations are already running.

Q302 Chair: We have heard evidence that there is a need to raise awareness in industry generally. Do you agree that quite a lot of industry does not yet recognise the potential for this technology?

Dr Thompson: Yes. The industries we have engaged with are outside those represented here. I would typically characterise it as their having a small number of quantum evangelists in the company, but in general their shorthand for quantum technologies would be quantum computing, and they think that is a long way away. However, we have shown through the study that we quite rapidly took a huge company in the UK from that perception to having detailed discussions with them about challenges they have now, and how quantum technologies in the next couple of years could help improve their margins. It is possible.

Q303 Chair: You could win people over quite easily.

Dr Thompson: We did, by getting in a room with the chief executive and the technology director. It is possible. The key message I took away from that is the importance of demonstrating proof of value, or the route to proof of value, for quantum technologies, rather than proof of concept, which is a natural evolution of what we are doing. That requires the technology and the industry communities to work more closely together. We heard time and time again about the importance of the supply chain and of a vibrant environment for commercialisation in the UK when major industries wish to step in; they may wish to acquire or shape the supply chain. The importance of standards, test, validation and confidence came out.

One more point is that one size does not fit all. Somebody said it earlier. Different sectors engage and innovate in different ways. Listening to those sectors about how they might better engage is incredibly important. I echo the comments about simulators. Allowing companies to operate in a simulated environment and test new capabilities is really important.

Q304 Neil O'Brien: Professor Cross and Dr Bentall, do you feel that there are adequate opportunities for industry to influence the national programme at the moment?

Dr Bentall: No.

Professor Cross: Not at the moment.



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Neil O'Brien: That is a short answer.

Chair: It is a very good answer.

Q305 **Neil O'Brien:** To all of you, how would you like to see industry input in the next phase of the programme? Would you like a new governance body? Would you like business on that body? What would you like?

Dr Bentall: We would like to see stronger industry, represented not just from the sectors that are here but from the other sectors as well, to make sure that their needs and opportunities to pull the technology through are really taken into consideration.

Professor Cross: I sit on the current strategic advisory board for the national programme, so I have seen this from the inside too. It is very much advisory and it does some good, but it does not have authority. It is very often informed about decisions that have been taken. It is appropriate now to move on to a different role because, as I hear from Sir Mark Walport directly, industry is being asked to step up and invest more. They will, but they will expect that the money they put in is directed to things that will have commercial potential. For part of the future programme—just part, not all of it—we should see a higher level of industrial direction.

I expect that even money spent in that way would still involve the academic base in a very major way. It is really the filtering process and the directing that will add value to the likely outcomes in sustainable wealth creation in the UK. An executive board with industrial representation, and possibly somebody with industrial experience leading it, and with a strong and very clearly and openly defined advisory structure, should manage all of the hubs, the CR&ND and the innovation centres and in some way inform the training programme.

Dr Shields: I agree with Trevor. Industry should have a stronger role in the governance of the programme. That would definitely be useful. I would also like to see industry contribute to the road map for the technologies. We could make a national road map that details when the applications will be realised and how the technology has to evolve to meet those applications. I would like to see much more engagement of industry in the current programmes. There is an appetite for that. Industry is ready to co-fund a lot of these programmes.

Q306 **Neil O'Brien:** Dr Thompson, is there any problem caused by Innovate UK's 30% limit on non-commercial organisations participating in projects? Is that a rule?

Dr Thompson: I know it has been reported previously by colleagues in Fraunhofer. I am not here to suggest a different rule, but 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.



Q307 **Neil O'Brien:** Could you give me an example? You might want to do what? When would the 30% rule be a problem?

Dr Thompson: An organisation such as ours does not have internal funding. Everything that we do comes from customers, so the 30% rule would make it very difficult for us to work on numerous projects. We are in high demand to support lots of industrial and other organisations because of what we can offer them.

Q308 **Neil O'Brien:** I am not quite clear what your solution was. You said that we should start by thinking about the right constellation of different organisations to work on something.

Dr Thompson: There needs to be some flexibility around the funding rules, and not being hard and fast at the point at which you open the competition, so that you get the right teams on the right programmes.

Q309 **Neil O'Brien:** That would seem to fit with the suggestion that Professor Cross made about having a single pool of funding rather than silos. Sorry, that was an observation.

Dr Bentall, in your written submission, you said, slightly surprisingly, that "existing funding initiatives are positively biased towards supporting SMEs." Why do you think that, and how would you like larger firms to be engaged?

Dr Bentall: From where we are, we are not necessarily looking at building the quantum technology box; we are looking at its application. By nature of the calls and everything that has gone so far, the funding has been more towards the industry sector that is taking the technology out of research and putting it into initial application. It has been difficult for us to access that and say, "How do I take that and bring it into its final useable application form, and has that then considered the needs and requirements?" We have seen a bias of funding towards that community—the next level up the stack—but not to the top.

Q310 **Neil O'Brien:** It sounds like you are saying that, because the funding is early-stage funding, the SMEs are more interested in that early stage, just coming out of the lab type of thing. Or is there more to it? When you say there is a bias towards SMEs, isn't that just the nature of what is being done at the moment, or is there something more to it than that?

Dr Bentall: No; we feel that we need to be there to try to influence the technologies that are coming out and how they are being matured. We invest in a huge range of technologies, the majority of which are very specific to our industry. Quantum technologies are very broad, so we do not put a huge amount of our own money there. All the multipliers we can get are of benefit, which brings me to the 30% question that you asked previously.

We do not prioritise research programmes just because they have co-funding. That is not what we are about. There is a cost to us in doing



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research that is in co-funded programmes of about 25% to 30%, so there is almost no net benefit to us financially. Therefore we do not get the multiplier on the investment we are putting in. We basically balance the cost of the engagement. Provided the cost of the engagement is what it is all about, that is fine, but 30% really is on the borderline. If it is anything less, we often do not do it; the cost is detrimental and the benefits do not outweigh it.

Neil O'Brien: It seems like a serious issue.

Q311 Graham Stringer: Professor Cross, you have been critical about the recommendations from the 2016 report on quantum technologies not being implemented. Can you tell the Committee which recommendations are still outstanding?

Professor Cross: It is more frustration that things have not been got on with a bit more quickly, particularly the one around governance. Although we envisage that it would be a really good idea to change the structure of governance for any second phase, it would not be a bad idea to implement it earlier and get things set up more quickly. That is the principal thing.

Q312 Graham Stringer: Do other members of the panel have a view on the speed, or lack of implementation of the recommendations?

Dr Shields: There has certainly been progress on some of the recommendations. I can comment on the ones about communications. There is work starting between QKD groups in the UK and post-quantum cryptography groups—two different communities. There are projects where they are working together, and I know that others are being set up at the moment.

We have started an accreditation process between QKD groups, the NPL and the QComm hub, which was another recommendation. There is progress, but we should recognise that some of the recommendations will take some time to realise. We are making progress in the right direction.

Dr Thompson: I would link the previous two comments: a single point of accountability through a new governance structure and ensuring that that single point of accountability is responsible for delivering against the recommendations of the 2016 study, and is held to account for it. That will accelerate the process.

Q313 Chair: Do you have some concerns about progress, or do you think that things are moving reasonably well on the recommendations?

Dr Thompson: Somewhere in the middle. There is definitely progress, but we would always like to see things accelerated more quickly. Sometimes it comes down to when funding arrives to do the activity. If you have a single point of accountability that sees that as a priority, the funding will flow very quickly.

Q314 Stephen Metcalfe: The development of standards for quantum



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technology is something we probably all want to see in tandem with the development of the technology. UKRI has suggested that those standards will be developed between the national programme and ETSI. Is ETSI the right organisation to be doing this with?

Dr Shields: It absolutely is. I chair the ETSI body, so I would say that. Definitely, for work in the communications area, ETSI is a very appropriate organisation. We have an ISG in ETSI that is working on QKD. We have 35 members, so it is a powerful group, and it is leading the standardisation of communication technology.

Q315 Stephen Metcalfe: And it covers all the areas that need to be covered in this field.

Dr Shields: It does, yes.

Q316 Stephen Metcalfe: For quantum comms.

Dr Shields: For comms, yes, that is right. The T in ETSI stands for telecommunications.

Stephen Metcalfe: Yes, it is the European Telecommunications Standards Institute.

Dr Shields: It calls itself ETSI now.

Stephen Metcalfe: Yes.

Dr Thompson: Quantum technologies will find their way into so many different industries that the existing standards bodies will be equally important.

Q317 Stephen Metcalfe: What will your role be in this, as the NPL?

Dr Thompson: Along with the British Standards Institution, we are the organisation that develops the measurement capabilities and sits on all those international committees. The key thing is to work with industry to shape the standards to enable UK industry to succeed in future. It is absolutely critical. The strategic advisory board last Monday raised the profile of the work on standards, and the importance of making sure that we are really doing that now, so that it does not become a risk in future because we are not implementing or shaping those standards.

Q318 Vicky Ford: My understanding is that a couple of weeks ago there was a vote in CENELEC, which is the overriding standards body for goods, saying that it wanted the BSI to continue to represent UK interests on that European body after we leave. It was also mentioned in the White Paper from Chequers that they want BSI to continue to have a role in the standard-setting bodies, which are of course non-governmental and away from Government. How important is it for the development of quantum technologies in the UK that you continue to have a role on ETSI? Can you see that continuing?



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Dr Thompson: It is very important. It is critical for BSI to continue to have that role. From the NPL perspective, we are part of a global collaboration; we are shaping international measurement standards, and BSI is influencing those documentary standards. It is very important that we maintain as high a profile as possible.

Q319 **Vicky Ford:** On both the European and the global body.

Dr Thompson: Absolutely. Global, yes. The markets for these folks are global.

Dr Shields: Yes. It is very important for our commercial interests, and the commercial interests of the UK in general, that we help to shape those standards in quantum technology.

Q320 **Vicky Ford:** Do the European standards tend to shape the global standards?

Dr Shields: Yes. Actually, ETSI is a global body, so within our standards body we have representatives from the US, Japan, China and all over the globe. It is not just European.

Q321 **Chair:** Dr Thompson, will the National Physical Laboratory's new quantum testing and validation facilities cater for all application areas? Do you hope to build more after 2019, and is there a budget in place for that? Was there industry consultation on what facilities to build?

Dr Thompson: I shall try to do the questions in order if I can remember all of them.

Chair: I will remind you if necessary.

Dr Thompson: Thank you. We collaborate with all four quantum technology hubs, and we lead a lot of the technology as well. You have heard about some of the collaborations. The test and validation capabilities that we are developing will be applicable to the whole suite of quantum technologies.

Q322 **Chair:** All application areas.

Dr Thompson: Yes. The new facility to which you referred opens in 2019—the quantum metrology laboratory. The increase in the importance of test and verification has happened since we first specified how large that laboratory would be, but I do not envisage that all the work will take place in that new building. It will take place elsewhere as well.

Q323 **Chair:** There are likely to be more facilities post 2019.

Dr Thompson: Yes; not necessarily new builds, but delivering that capability. Our presence is regional and national across the UK, so we would look to work with colleagues in the hubs and industry to conduct test and validation.

Q324 **Chair:** What about the budget for those facilities?



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Dr Thompson: The budget, or certainly some of it, will be part of the future national quantum technologies programme.

Q325 **Chair:** It is dependent on what happens this autumn.

Dr Thompson: Yes.

Q326 **Chair:** The other question, to remind you, was whether there was industry consultation on what facilities to build.

Dr Thompson: One of the reasons why I shall not be very good at answering that question is that I was not around when that consultation took place.

Chair: That is a reasonable excuse.

Dr Thompson: Trevor, who was certainly involved, will know whether there was industry consultation at the time.

Professor Cross: There is, at least through the hubs. For example, in Kai's hub, more than 100 companies are involved and more than 30 have active, funded collaborations, so there is a lot of awareness in the hubs of what needs to come next. Probably we could do with augmenting that, now that we have gone several years down the line; it was three years ago, if I remember rightly. Broadly there is a lot of interaction, and the awareness is quite shared.

Dr Shields: We have a project with NPL building processes for security evaluation of quantum communication technology, which is funded by Innovate UK at the moment.

Q327 **Carol Monaghan:** Professor Cross, in your submission you talked about the need to develop skills that were not necessarily academic. We have already heard this morning about technician-level skills. Are there other skills? How would you envisage them being developed? Do you think that the national programme is not developing those skills properly?

Professor Cross: The national programme has been fantastic; we would not even be here if it was not for that. What can we do even better? For example, in building up my team from three to 33 over the last five years, I have one German, two French, whom I personally recruited from Bordeaux University, one Turkish, one Polish and one Irish. They are the core of the new IP that I brought into the company, the new knowledge. That is mainly harvesting at PhD level, so we need to be able to continue to do that. Actually, I would like to see us stuff more people into the pre-PhD STEM pipeline. That is something that we have to do for a whole load of things, not just quantum.

In quantum specifically, some of the most valuable people in terms of output and stickability in my company are technicians. We would like to see some way of quantumising—giving some quantum skills—to those technicians. I am thinking about more continuing professional development and short courses. I would like my already degree-qualified



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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.

It is pretty much across the patch, even apprentices. I have two apprentices working in my team of 33, and they are terrifically valuable. We should not underestimate the draw and appeal of quantum—a bit like space 30 years ago—and getting people into a factory that is established and where some of the technologies are mature. This is something new and shiny, and very future-oriented; it is a great draw for people.

Q328 Chair: To go back to your earlier point about the international team you have recruited, we have a report coming out soon on the immigration rules that we believe are necessary post Brexit for science and innovation. Are you making the point that it is really important for us to be able to continue to attract the best people at whatever level?

Professor Cross: Yes, I am making that point. Science has been international for decades; we all know that. Some of those international people have come via their PhD placements in UK universities; they look around and say, “The UK is a nice place to be, is there any employment capability?” and they jump over to work for us, while sometimes still working with the university. But I have had to go outside the UK to recruit people. I am not negative about that; I think it is brilliant.

We want the best people, and how we attract them is, yes, partly through the company, but also through the fact that there is a great ecosystem in this country if you are interested in quantum technologies. Bright people migrate to where the best programmes and the most interesting things are. One of my jobs in my factory is to make life for my workforce interesting and challenging all the time, not just for quantum but across the patch. Maintaining bright people doing interesting and challenging things to make money for us is where we are at. This is the knowledge-based economy that we talk about; it is an old phrase, but it is a really important thing.

Dr Thompson: Right the way through the spectrum, from apprentices to PhDs, that is critical. Through the exercise that we ran 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.

Q329 Carol Monaghan: Do you think that there has been enough opportunity for industry to feed this into the programme? We heard from Dr Graeme Malcolm of M Squared Lasers, who said that he felt industry was not being listened to.

Dr Thompson: Certainly, since my involvement in discussions about the programme, the industry voice, and the importance of the industry voice,



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has always been present at the strategic advisory board. Now is the time to make sure that industry's voice shapes the programme.

Q330 **Carol Monaghan:** At the moment, is industry able to direct the skills mix that is needed in this programme?

Dr Thompson: More no than yes, but if you address the governance, and have industry on the advisory board and the executive board, it will be able to do that.

Professor Cross: Right now, the answer is, "Not well enough, no." It is listened to and it is heard, but it does not have the authority.

Q331 **Chair:** That needs to be addressed before the second phase.

Professor Cross: Yes, it does.

Q332 **Carol Monaghan:** Dr Thompson, I believe you have supported 30 PhD studentships in quantum technologies at NPL.

Dr Thompson: We are up to 40.

Q333 **Carol Monaghan:** Maybe I could direct this question to the other three. What would encourage your organisations to support PhD studentships through quantum technologies?

Dr Shields: We already support a lot of PhD studentships through the CDTs—the centres for doctoral training. They involve industry quite well and have a lot of industry engagement; we have a lot of secondments in our company as well, and we co-fund many of those studentships. That programme is quite good, and we should continue with it and concentrate those CDTs in applied engineering areas; that is where we have a skills shortage.

Q334 **Carol Monaghan:** Are you supporting any PhDs in the hubs at the moment?

Dr Shields: The hubs do not employ PhDs directly. They come through the CDTs, and a number of those are in the quantum area. The Bristol, UCL and Cambridge hubs support PhDs in the quantum area.

Q335 **Carol Monaghan:** Are there any further comments?

Professor Cross: In the area of imaging technology, we are a bit more established. We have a running business worth £25 million a year based in the UK, in Chelmsford. In that area, we work with the Open University, and financially support a group that includes 22 people overall, most of whom are PhD students. We co-fund a chair at that university. Those are the sorts of things that are possible when we have an established business.

Right now, we are investing very heavily in my core team and collaborative co-location. That does not include many PhD studentships; I think we might have one. When we get to the point of starting to sell



products, we can move on to other models. That is kind of peculiar to our company, but it is kind of on our road map. What would make it easier is a bit more flexibility around when we can dip in and make those sponsorship decisions. The CDTs work best if you get in at the beginning, which means once every five years when the CDTs are refreshed, so there is a lot of demand at the moment. 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.

Q336 Carol Monaghan: Dr Bentall, in terms of big business, how do you see it?

Dr Bentall: We have a few PhDs in this area, but it is a few, and it is driven through the programmes we are currently running—again, a few—which is why having more programmes is also positive in this area, because then they work directly on projects and activities.

To go back to the skills mix, we are really just touching on that end of things, and more can be done. It is in the other areas—the technicians, the engineering skills and the core—that we need to get quantum skills into the standard programmes on communication engineering.

Q337 Carol Monaghan: Do you see it as more of a role for SMEs and academia to deal with PhDs than for big business?

Dr Bentall: Not necessarily, but it is about the skills mix. We have more PhDs in that area of application. You will find a lot of aeronautical engineers with PhDs rather than quantum engineers. That is partly the problem: we need to be able to communicate in the right language with academic institutes and the SME community, so that we can understand the technology and put it into application.

We have a role, but it will probably not be as big as the academic and SME community's role in that particular area. Where we need an improvement is in the core engineering workforce. In Airbus Defence and Space, we have 8,500 engineers, very few of whom understand quantum technologies and how they can exploit and use them. That is the workforce we need to bring up to speed.

Q338 Carol Monaghan: I want to take you back to something you said earlier; you were unhappy about the level of funding that went into SMEs and academia. But you are saying that you are not really supporting PhDs in this area, particularly in quantum technology.

Dr Bentall: We are, through the limited engagement we have.

Q339 Stephen Metcalfe: Dr Bentall, in your written submission you talked about using challenge-based programmes to develop quantum skills. Could you expand on that a bit?

Dr Bentall: Yes, it is something that was discussed earlier—having more of a challenge on a particular application or target, and having a more



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significant focus to really drive it through. The point made previously was that in this country we are great at developing technologies, but we need to make the innovation step to bring them to market, with more focus on the end application challenge. I am not saying that it has necessarily to be in our sector—we are just one sector—but that would be our preference.

Q340 Stephen Metcalfe: Do you see that standing as a separate challenge programme, or could it sit alongside the supply chain?

Dr Bentall: It could sit alongside it; I do not see why not.

Q341 Graham Stringer: Are there any particular opportunities or risks associated with Brexit?

Dr Thompson: I see the opportunities around thinking globally. We are in an international race in quantum technologies. To quote Graeme Malcolm, it may be a 10-year race that we want to win by two weeks. Other nations around the globe are investing hugely. The proposal is to give our counterpart in the US, NIST, \$400 million to help to support their side of the business. The opportunities are around the global market and thinking globally.

The challenges are the usual ones of attracting the best skills to the UK, and some of the uncertainty that that generates, but that is no different from other areas of science and technology.

Q342 Graham Stringer: Anybody else?

Dr Shields: Obviously, there are the risks of losing key personnel. We have a large team of around 30 or so researchers.

Q343 Chair: In the UK.

Dr Shields: Yes, in the UK. At least half of them come from the EU. If they all left tomorrow, it would be disastrous for us.

Q344 Chair: I guess it is also about the flow of new people coming in. You would be concerned about that.

Dr Shields: Yes, but it does not seem to have affected us yet. We are still attracting new researchers from the EU.

Q345 Chair: But, in the design of the rules post Brexit, is it an important thing for you to be able to continue to attract people from the EU?

Dr Shields: Absolutely. We want to be able to attract the best talent from the EU and from outside the EU. We absolutely need to, in fact.

Professor Cross: If the barriers are slightly higher, it will not deter people who want to come and do the best internationally interesting science and technology in their careers, as long as there is a way. If it is slightly more difficult, that is annoying, but it will not stop people. I am



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more concerned about boosting the overall pipeline of generic S&T skills across the whole area of electronic activity.

Q346 **Graham Stringer:** That neatly leads to my final question. Is there any policy that the Government should change in relationship to this sector post Brexit?

Professor Cross: It kind of overlaps with the last question. I would want to be absolutely certain that we continue to co-operate in EU programmes. We have just won a quantum flagship initial programme, so that will endure, and we have commitments there.

Q347 **Chair:** Is it through Horizon?

Professor Cross: Yes, through Horizon 2020. It is a sign that we are internationally competitive, and we want to stay that way. Science has been collaborative for so long, and that fact is not going to change because of Brexit, but the smaller the number of hurdles, the more successful we will be.

Dr Thompson: It is not a policy change, but an opportunity. The lens and the focus will be on us in 2019. What a great opportunity to show the world that we are world-leading in science and innovation, and that we are serious about commercialisation.

Q348 **Neil O'Brien:** I have a two-part question. First, can the panel give us a quantification of roughly how much is being invested in other countries and how much is being invested in quantum research in the UK? Secondly, I have a fear that, despite our early lead in some of these different fields, the fact that others are investing an awful lot more will be telling over the longer term. Am I wrong to fear that? Various people have mentioned some numbers.

Professor Cross: I have never been afraid of the Americans, because, first, we get on with them and, secondly, we get far better value for money. We have £4.5 billion of investment going into the academic base in research funding across the whole economy, yet we continue to over-perform in citations and publications. Let's do the same thing in innovation, and change how we support and nurture innovation.

Q349 **Neil O'Brien:** Is there any quantification of how much, roughly, total spending is in the quantum space in the UK?

Dr Bentall: From the numbers I have seen, I think we are about fourth in the global picture, with the US, China and Germany above us in terms of spend.

Q350 **Neil O'Brien:** What is the source for that, roughly?

Dr Bentall: There was a publication—

Professor Cross: I think there was something in the Blackett review.

Dr Thompson: There was a McKinsey report.



Neil O'Brien: That is the most recent good data.

Q351 **Vicky Ford:** I just want to ask you again, to check what you said on Brexit. If there was a no-deal Brexit, and no agreement on the withdrawal agreement, so there was no right for your EU citizens to stay in the UK, no deal on trade and goods and no continued co-operation in Horizon EU, would that be fine and upside, or are you saying that it is fine provided we deliver a deal that keeps rights for your EU citizens to stay, and includes trade and goods and co-operation in science networks?

Dr Thompson: Personally, I would prefer not to have a no deal.

Dr Shields: No deal would make life difficult. We have a lot of EU employees. I am sure we could get visas for them under a new scheme, but it would make life a bit more difficult. We also have a lot of collaborations in Europe, which are an important part of the supply chain and which obviously we would like to keep.

Professor Cross: It would be deeply difficult if my European colleagues who work with me upped and left, but I do not think they will. It might hinder the rate at which we could recruit more.

Dr Bentall: It would be a similar problem.

Q352 **Chair:** Before we finish, are there any final messages, as we think about shaping our report, for our advice and recommendations to the Government? Is there anything that you think is important for us to take on board?

Professor Cross: Somebody—it might have been Neil—asked whether we should put more into the areas where we are strong or whether we should be broader. We should look at the ecosystem around us and ask where we already punch above our weight. We know that we are going to have a space launch capability in this country. For decades, we have punched above our weight in that area, and there is an overlap with quantum technologies and capabilities in space, in many different ways. Let's really go for that. That would be such a good catalyst to broader economic activity.

We would not do imaging in the UK today if we had not got involved in things like the Envisat programme. Today, we have 20 million in space, but we have 80 million in non-space that would not be there if we had not engaged in that space programme early on.

Q353 **Chair:** Any other comments?

Dr Thompson: Let's keep our eye on the prize: jobs, tax revenue benefits to society and, along the way, contributions to the 2.4%, and inward investment in the UK.

Q354 **Chair:** Presumably a timely decision on funding for phase 2 is critical.

Dr Thompson: Yes.



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Professor Cross: I forgot. There is one final thing. Now that I am part of the Teledyne group, I have found that the quantum activity we have in the UK is causing the group as a whole to look at making the UK the centre of all its activities. We could well see, if things continue to go in the right direction, some inward investment in ways I had not anticipated.

Q355 **Chair:** That is encouraging. Good.

Dr Shields: Industry has real appetite to invest in this area. People see new products and applications coming out in future. Let's think how we can better integrate what is going on in academia with what is going on in Government labs and industry in future.

Chair: Thank you all very much indeed. We really appreciate it.