HOUSE OF COMMONS

Science and Technology Committee

Oral evidence: Quantum technologies, HC 820

Tuesday 5 June 2018

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Watch the meeting

Members present: Norman Lamb (Chair); Vicky Ford; Bill Grant; Darren Jones; Liz Kendall; Stephen Metcalfe; Carol Monaghan.

Questions 1 - 134

Witnesses

I: Professor Sir Peter Knight, Emeritus Professor, Imperial College London; and Professor David Delpy, Chair of the Strategic Advisory Board, National Quantum Technologies Programme.

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

Written evidence from witnesses:

- Professor Sir Peter Knight
- Institute of Physics
- Royal Academy of Engineering
- UCL Quantum Science and Technology Institute
- Dr Ashley Montanaro

Examination of witnesses

Witnesses: Professor Knight and Professor Delpy.

Q1 **Chair:** Welcome, both of you. Thank you very much for being here. Could you introduce yourselves briefly?

Professor Delpy: I am David Delpy, emeritus professor of biomedical photonics at UCL. For the purposes of this Committee, I chair the strategic advisory board for the national quantum technologies programme.

Professor Knight: I am Peter Knight from Imperial College, emeritus professor of quantum optics. I am also the interim challenge director for the industrial strategy challenge in quantum technology and a member of David's SAB.

Q2 **Chair:** Thanks again. Perhaps we can start with what is a quantum technology?

Professor Knight: The easy bit.

Chair: Along with that, what can quantum technologies do differently or better than non-quantum technologies?

Professor Delpy: I will start, but Peter is the quantum expert. I would ask the question the opposite way around: what isn't a quantum technology, since everything is made up of atoms, which, of course, obey quantum laws? The unique thing about quantum technologies is that they are a way of approaching the real, fundamental limits of measurement and sensing, and of enabling you to do things that, in the non-quantum world—the practical engineering world—seem impossible at the moment, but that physics has always said are theoretically possible, and that we can now start to engineer and achieve. Peter, is there anything you want to say specifically about quantum?

Professor Knight: With this initiative, we are looking to harness parts of what quantum enables us to do that we have not been able to harness previously. After all, we have been using quantum in lasers, semiconductors and so on for many years. They are quantum enabled, but they do not necessarily exploit what is called quantum coherence. Quantum coherence is the weird ability to put things into superpositions of both here and there. That is really hard, because it talks to the environment really effectively the more you pile them in. That is what makes a really great sensor. Defects in one place become advantages in others. In the programme, we are working out ways in which we can get a technological application of the oddities of superpositions, entanglement and so on. That is why sometimes it is called quantum 2.0. It is the next stage.

There are places where you use this all the time. If you use sat-nav to get here—you probably don't, but if you did—it works with atomic clocks. Atomic clocks are little atoms that process around in a coherent superposition and give you a timing. You already use all the little quantum bits that we are trying to harness, in your clocks. What we have to do is to harness lots of them to give you this new ability.

Q3 **Chair:** That is what is different—the add-on to what we have been doing for some decades, I guess.

Professor Knight: Yes.

Q4 **Chair:** What is behind the current increased interest? What has led to that next stage?

Professor Delpy: In the first instance, what led to it is long-term underpinning funding by the research councils of quantum physics for research in the quantum science area. That has led to the point where we have a real understanding of what enables you to achieve a state of superposition or quantum interference in the laboratory. That has coincided with developments in engineering and nanoscience that, for the first time, give us the hope that we can take this very sensitive state out of the laboratory and engineer it to the point where it is just a block—a bit of instrumentation, with a power connection and an on-off switch.

Once quantum science has reached that point, it can be used by the rest of the world. You will not need a degree in quantum physics to understand how these things operate. The quantum technology programme is really all about engineering the basic quantum science, in which the UK has phenomenal strengths, and creating an industry around what was previously a laboratory phenomenon.

Q5 **Chair:** There is a range of new quantum technologies, with a range of different applications. Is there enough commonality for it to make sense to consider them together? You are nodding, Sir Peter.

Professor Knight: One of the things we work really hard on is a road map of where we need to do long-term investment to get something really substantial. Basically, that is quantum computing. On that journey, which is at least a decade long, what can you do to exploit the advances you develop en route? Part of what we are doing, en route to that bigger machine, is working on things that are of tremendous advantage already. I mentioned the fact that, when you are trying to build quantum bits to make a computer, they are very fragile, because they talk to the world. That is what you need in a sensor.

I have been calling it oven ready. We already have devices that are ramping up the TRL scale and will become really useful: for example, we can already harness the kind of quantum interference that we are using in a quantum computer to work out where the buried infrastructure is in the road. Half the holes in London are dug in the wrong place, because we do not know where the pipework is; it costs billions per year. If we increase the sensitivity by a couple of orders of magnitude, a couple of metres probably, we will know where that is. The quantum bits that will do that sensing are the ingredients we need for a quantum computer en route, but we will get it earlier. Imaging, sensing and quantum communications are all developing from bits of the supply chain that provide the bigger vision. There is a coherence to it.

Professor Delpy: The difference between quantum science and a real quantum industry is the standardisation of components, subcomponents and elements. In fact, one of the key things about the programme that we put in place is to try to ensure that we develop a series of standardised elements—building blocks that are easy to engineer and can be used in a variety of applications. That is how you get real, rapid progress, and reductions in cost. As you know, once you have a standardised integrated circuit, you can use it in all sorts of applications. The moment you have a standard miniature atomic clock, you can start to build it into anything. That standardisation is a key component of the engineering of quantum science.

Q6 **Chair:** You have given an indication of some of the impacts on society. Could you say a bit more about the societal impact of these technologies?

Professor Delpy: You are probably aware of the fact that, as part of the programme, we held a public dialogue on quantum technologies, to see what the public thought of them. We held a series of four workshops, with members of the public meeting the four hub research groups. Interestingly, what came out of that was that there was a real interest in what quantum science was. There was not what I was worried about, which was a fear about the spookiness of the quantum phenomenon.

In the end, the thing that came out of our report was that the public felt that this was just a natural progression of what has happened with a whole range of technologies. In general, there were not that many things unique to quantum that they were particularly worried about. The only thing anybody was really aware of was the potential for quantum cryptography and for the breaking of current secure software systems. Otherwise, we were very pleasantly surprised to find that the public were really supportive of the technology and its happening in the UK. They felt that everybody could benefit from it.

Q7 **Chair:** Peter, do you have any additional comments on the big societal impacts?

Professor Knight: What will we generate within the national programme that will affect everyday life? The biggest single thing I would point to is that, basically, we have to assume that the encryption we use to secure the internet will fail within the decade. RSA—public key cryptography—will be dead within a decade because of the advances in quantum computing technology. All the things we do when we use HTTPS for secure engagement—trading, commerce, entertainment and securing our own identity—have to be rolled up in a replacement within a decade. That is the big impact we have to deal with. That is why every single part of Government is engaged in this. We know that it takes a fair bit of time to replace public key cryptography, maybe a decade. What is the threat time? About a decade. When do you start thinking about the roll-out? About now.

Q8 **Chair:** Do you think that enough progress is being made? It has been described as the crypto-apocalypse, hasn't it?

Professor Knight: I am sorry; I invented that word. It does enrage people.

Chair: What progress are we making towards avoiding the apocalypse?

Professor Knight: There is a lot of work going on. There are two routes forward to replace this, so that we can secure the integrity of the internet. One is called quantum-safe or post-quantum encryption. Some of the leading young people in the UK are working on that. You will hear from one of them later on; I think he is sitting behind me at the moment. At the same time, we have what is called quantum cryptography as a replacement. We are rolling those two out together and road-testing them, to see what we can do. The UK has a tremendous advantage in this area, because British Telecom, one of our major suppliers of that sort of national infrastructure, is fully engaged.

Q9 **Chair:** Do you feel confident that we will avert the apocalypse?

Professor Knight: Yes.

Chair: That is encouraging.

Professor Knight: Provided—there is always this thing—that we do not lose our nerve on the funding of the national programme.

Chair: That is critical.

Q10 **Darren Jones:** We might protect the internet in the UK, but this is a global issue. How are we co-ordinating around the world on getting it right at the right time?

Professor Knight: For that, we have to make sure that we have put in the appropriate standards and validation of systems. There is worldwide activity on that, under the banner of a thing called ETSI. The chair of the working group on that, which is an international working group, is Andrew Shields. He is part of our national programme and runs the Cambridge Toshiba operation. The National Physical Laboratory and the National Cyber Security Centre are fully engaged in this. We have an edge, particularly because we have joined up these two parts: quantum-safe encryption, which is classical, and the quantum cryptography stuff.

Q11 **Chair:** We should not assume that that is there for good. We have to protect it and to invest in it.

Professor Knight: And we have to grow the community that works in it. We know perfectly well that suitably qualified and experienced personnel in this area are hard to get hold of. In the big international race to develop ways of doing this security, we need to make sure that we have the skilled people and retain them.

Q12 **Chair:** David Delpy, the national programme has what is called a responsible research and innovation framework. How does it aim to address the range of potential adverse impacts of quantum technologies on society?

Professor Delpy: The RRI—the responsible research framework—is something that all the research councils require of programmes that are being funded. It was specifically a remit of the four hubs that we funded. In fact, in their original bids, they had to describe exactly what they would do to enable it.

Each of the hubs has run its own series of RRI workshops, and through EPSRC, there has also been an RRI programme. In fact, UCL, which you will hear from later, has run, together with Oxford, a whole range of semi-public dialogues on this area. We have made sure that, as part of their programme description, all the researchers in the hubs identify the potential social implications of their research. We are open about that and try either to address it or to put in place any mitigations that are needed. As I said in the discussion about the public dialogue, there have not yet been any adverse impacts that we have had to address, but we have made sure that the research groups involved are very aware of it, and it is part of their key programme.

Q13 **Liz Kendall:** How do we compare internationally? What are our strengths and weaknesses in this sector?

Professor Delpy: Internationally, the UK can say that it plays extremely strongly, in particular because of the strength of the integrated programme that we have. We have a very strong science base. In fact, I am sure we got the original £270 million funding because of that. The allocation of the funding for the quantum technology programme triggered awareness of the potential of quantum technology around the world. After we had our programme up and running, we saw the EU respond very quickly. It has a flagship coming up at the end of this year. The Americans immediately put another $50 million into their existing programme, and they have now put in additional funding. The Netherlands, at Delft, has made available very significant funding of international programmes, as have the Canadians, the Australians and Singapore.

I would say that, at the moment, we are still world leaders, particularly in an integrated programme. There are some scientific areas where, to be honest, we are not leading. Originally, we got 17 bids for funding. We shortlisted eight of those and then selected four hubs. We deliberately chose bids in areas where we felt the UK had an international lead, rather than put in funding to try to build up the areas where we felt there was a weakness. We felt it was much more important to ensure that, where we had a lead, we built on it and maintained it.

Q14 **Liz Kendall:** It is a bit like Olympic funding: you have to be great to get the cash.

Professor Delpy: Yes.

Q15 **Liz Kendall:** You said that we are very strong on the science base. How do we do on getting science into practice and commercialisation?

Professor Delpy: Obviously, we are not as good. It is difficult to judge, because there is no quantum industry. It is unlike areas such as aerospace, the motor industry and so on, where there is a sector council that can identify for you how many jobs there are and what the potential future is. What we are doing is building an industry. At the moment, the industries are predominantly manufacturers of subcomponents—assemblies that go into quantum-enabled measurement instrumentation and machinery. We are building an industry.

The UK is very strong on the number of companies that have key technologies in this area—lasers, cryogenic equipment and so on. What we are lacking, to be honest, is a major systems integrator. We do not have the equivalent of a Siemens or a Philips. We have some big strengths in the defence area, with Airbus, Thales and so on, but we are missing the large systems integrator. However, we are very good at making the components.

Professor Knight: Can I chip in? When we looked at our strengths, as well as identifying where the scientific strengths were, we had to work out where there was an industrial appetite to get engaged with us. Vicky has heard me say this before, but photonics is the key to a lot of this stuff. A lot of the enabling platforms that we use hinge on photonics.

Q16 **Liz Kendall:** What does that mean?

Professor Knight: It is the use of light and lasers to manipulate and detect things. Usually, it is light as the engine for these things. Carol has also heard me say this before, but photonics contributes more to the GDP of the UK than pharmaceuticals. Very few people knew that before we started to do the numbers. It is in 1,500 companies. It is the enabling technology to do so much. It is one of the strongest parts of our manufacturing sector, so the platforms that we will exploit in the four hubs all have a photonics component. As well as getting really strong academic strengths to push it forward, there were companies that had an appetite to pick it up and run with it.

Professor Delpy: Not having a large existing industry, we recognised that, if we were to have a technology programme to try to develop an industry from scratch, we needed industry involved right from the outset. In the original call, it was a formal requirement that the hubs putting in bids had to be consortia of universities. We were not going to fund single universities; they had to be consortia, and not only did they have to have industry involved in them as consortium members, but they had to have evidence that industry was part of the development of the original call. We required industry to have been involved in the development of the call for the hub. In fact, when we did the final interviews, one of the three members on the panel from each of the hubs had to be an industrial representative.

Q17 **Liz Kendall:** It is focusing on our strengths rather than addressing weaknesses, and industry has to be involved.

Professor Delpy: Yes.

Professor Knight: Yes.

Q18 **Liz Kendall:** Is the method that the national programme is using different from the method used by the research councils?

Professor Delpy: The answer is yes, because this is not a science programme. The research councils have run very large science programmes, and continue to do so. Industry is usually heavily involved in them, but they are driven by a series of academic questions, of grand challenge from the academic point of view. This is a technology programme. Although in the first phase it builds very strongly on an academic base—we have always said that it is a 10 to 15-year programme—the second phase has to be very much industry driven. We need industry to be in from the outset, which it has been, and the second phase we are proposing must have industry in the driving seat, but you have to continue to fund the basic science. In this area, the moment you solve one engineering problem, you come up with another basic science question that you have to solve for the next engineering problem to be solved.

Q19 **Liz Kendall:** Some people have raised concerns about delays with project starts by Innovate UK and have said that it can be a bit bureaucratic. Are you aware of that? Have those underlying issues been resolved?

Professor Delpy: They have. I am aware of the problems that happened early on. One of the advantages of the programme, yet one of its disadvantages, was that the money was allocated at relatively short notice and we had to get spending quickly. That worked to the advantage of the community, because there was no time to split up and decide that everybody wanted to do their own thing.

We ran a very short and intense national programme. The disadvantage of that short programme was that we had to put the money through existing organisations. The majority of the funding went through the EPSRC route, while £50 million went through the Innovate UK route. The EPSRC was well geared up to run large-scale programmes. Innovate was going through a very difficult period. Its budget had not been set, yet it got that additional funding, so Innovate stuttered a bit at the start, not for reasons relating to quantum technology, but because of the timing of the programme. In fact, it got up and running extremely well, thanks to a couple of really good members of staff who have done a fantastic job, given the relatively short timescale they had to get the programmes up and running. It is often slower to get industry-related programmes up than academic ones, where the research groups are already there.

Q20 **Liz Kendall:** The Government Office for Science ranked the UK third in the world for investment, research and commercialisation. The US, China and Germany are up there. What would it take for us to be No. 1?

Professor Delpy: To be honest, I suspect more money than we are likely to get.

Q21 **Liz Kendall:** Aim high. What would it take to make us No. 1?

Professor Delpy: We are aiming high. What we need is a continuation of focus, as we said. We should not try to be No. 1 in terms of spend. We need to identify the key areas of strength—the things that will underpin this new industry—and focus on them.

Professor Knight: We want to be No. 1 in areas where we know we have a lead. We are not going to be No. 1 in every single piece of quantum technology, but we want to make sure that we are No. 1 in quantum sensing and quantum imaging. To be honest, we have a platform for quantum computing that is the only one in the world that is scalable.

Liz Kendall: Sensing, imaging and computing.

Q22 **Chair:** David, you said that we lacked a systems integrator. Does that matter? Is it just a fact of life, or are there efforts under way to encourage and promote the development of such a beast?

Professor Delpy: Does it matter? At the moment, it does not, because the key elements of quantum instrumentation, quantum machines and so on are the subcomponents. At the moment, there is not a single instrument, apart from quantum computing, that is a quantum instrument. Instruments contain a quantum element. At the moment, we are developing the companies that can make those.

The UK ought to have some large-scale systems integrators. The way we are developing the programme is the best way of attracting those.

Q23 **Chair:** The way the programme is shaped, beyond the current time phase, will be critical to that, won't it?

Professor Delpy: Absolutely. Once you have some standard building blocks that an automotive manufacturer can build into a modern electric car—a whole range of quantum-based sensors—it will want to work with the groups and components manufacturers that can make those. We will attract systems integrators once we have those simple engineering modules.

Q24 **Carol Monaghan:** I want to ask about risk. Professor Delpy, you said that we cannot be No. 1 in every area. Are there any particular areas of quantum technology where we must not be left behind?

Professor Delpy: Interestingly, computing is the one that I would flag up. Right at the outset, we decided that we would not fund a hub whose major aim was to develop a quantum computer. We felt that was too long scale. At the moment, there is a whole range of competing technologies, and no one is quite sure which will be the winner. What we did—the Oxford group— was to identify a technology that, as Peter said, is scalable. One of the key things about early work in quantum computing is being able to get to an adequate scale really to start to test some quantum areas.

We are doing well in the ones we currently fund, as long as the programme is continued and the additional funding we are asking for comes through. The thing that we possibly misjudged, to an extent, is the rate at which the quantum computing area has changed and developed. We need to make sure that we do not slip behind in that. We have some fantastic expertise in diamond-based quantum computing in the UK. We have some great skills in the scalable quantum module. That is the area where I would not want us to slip behind.

Professor Knight: I agree entirely.

Chair: That was a very quick and precise answer, Peter. Thank you.

Q25 **Bill Grant:** I note that Sir Peter said that we must not lose our nerve on funding. My question is on that area. Gentlemen, are you aware of any commitment from the Government to extend the national quantum technologies programme beyond 2019? I understand that it is funded until then.

Professor Knight: When we started, I talked about a 10-year vision and five years' funding. I think the appetite is there to continue the engagement. There is a warmth about the area when we talk to the various component parts of the funding ecosystem. We need to translate that warmth into a rock-solid written commitment in the Budget this year, but I think the appetite is there.

We are in the middle of a lot of quite delicate negotiations. I have written a vision piece about why, which has gone to UKRI. Mark Walport asked me to produce that. The strategic advisory board, working with the component parts of our system, has written a very detailed business case, which BEIS and the Treasury are working their way through at the moment. We are at the stage where they are looking at the detail, but I think the appetite is there.

Q26 **Chair:** The key moment is this autumn.

Professor Delpy: Yes. It is absolutely essential that a commitment is made by the autumn. We made sure, as a strategic advisory board, that the bid was in before UKRI was officially formed on 1 April. To be honest, if we do not have a formal commitment by the autumn, a large number of the academic groups and industries that have built on the existing programme will see that in one year's time it may all disappear, so we will lose everything we have built up.

Professor Knight: Exactly.

Professor Delpy: We need an early commitment to continuity.

Q27 **Bill Grant:** That will influence the retention of the expertise you require.

Professor Delpy: That's right.

Professor Knight: Especially when the rest of the world is trying to ramp up and catch up with us.

Q28 **Bill Grant:** The same gene pool of expertise is in great demand.

Professor Delpy: Absolutely.

Q29 **Bill Grant:** Taking that a stage further, do you require a similar amount of funding for the next stage, which would, hopefully, be for five years? I think it was £270 million over the previous five years. I am not asking you to give figures away.

Professor Knight: It is of that order. Let us not focus too much on the £270 million. It is actually running at nearly £400 million. The reason is that other partners have come in and made a co-investment, which is one of the big strengths.

Q30 **Chair:** Private partners?

Professor Knight: There is an element of industrial commitment, not just of cash, but of resource and new appointments. The National Physical Laboratory has put substantial resource in to build the Quantum Metrology Institute, which I chair. There are other investments. The Ministry of Defence, through DSTL, has derisked some of the early prototype development, for example, where we can see that there is a dual use for things. Keeping those partners fully engaged has been critically important for us.

In our business case, there was a rough-and-ready figure for the number of parts that we put together. We wanted to protect the skill base, the research base and the innovation centres that we have in mind. It comes out looking very precise—£338 million—but the component parts had error bars on them. That is the scale we pushed for, because that is what we believe we need. The balance between the parts is very different from phase 1, because you will see industry engagement and innovation centres being a bigger part of it in phase 2.

Q31 **Bill Grant:** I think you have answered my next question. The 2016 GO-Science report recommended matched funding from industry for phase 2 of the national programme. Has that been met and, maybe, exceeded?

Professor Delpy: The bid we put in indicated about £200 million of matched funding to the £338 million that Peter mentioned. It is difficult to judge the actual commitment, because a lot of it is in kind and in the time of industrial collaborators. To be honest, it would be unfair, when we do not have an industry, to say that we need matching funding from the industry. It is quite clear that we will meet and exceed the £200 million that we talked about in the phase 2 bid. In the original bid—the £270 million we bid for—we did not anticipate that industry and others would leap that up, effectively, to the best part of £400 million.

Q32 **Bill Grant:** You mentioned that we cannot be No. 1 in all the arenas of quantum technology. Do the matched funding providers to date influence certain aspects that could leave the less well-developed behind? Is that a risk or a concern, or is it accepted?

Professor Delpy: The answer is that the matched funding, phase 2, must be driven by industry to a much greater extent.

Q33 **Bill Grant:** With a commercial application as the outcome.

Professor Delpy: Yes. It must identify the areas in which it feels that there is a real commercial business case. However, the downside of that, of course, is that some of the fundamental science may get left behind. That is not the case either with the existing programme or with the future one, because we have always separated very deliberately the funding of the basic science, which EPSRC has done for 60 years and is continuing to do.

In fact, one of the problems that I suspect EPSRC is now facing—I used to be the CEO there—is that the growth of the quantum technology programme has increased the number of academics who are working in the quantum area and are, therefore, bidding to EPSRC for fundamental science projects. A consequence of £270 million going into quantum technologies is that there is increased demand on the academic side for basic quantum science development. We need to ensure that that grows. The EPSRC council has been very clear that it wants to continue to commit to that, but that depends on its budget.

Professor Knight: Some of the brightest young people look at this and see that they can make a fundamental advance in their science and that it will have an impact on everyday life. If you look at the recruitment of PhD students and others, we are being overwhelmed by young people who want to be involved in this adventure.

Q34 **Bill Grant:** I like the national programme being described as an adventure. We mentioned that one company, BT—I am sure that there are more—was fully on board and you seemed quite enthused by that. Is there a problem or an issue that, when these companies are on board, they may over-influence the direction of the national programme, or is there a balance that can and is achieved? Are they pulling it in a direction? Who is at the helm to spin things that spin both ways?

Professor Knight: On the industrial strategy challenge fund part of it, I guess I am, because I am the interim challenge director. I have found that, at this early stage, companies are pretty collegiate. They are not trying to outmanoeuvre one another. They can see that, if they come together on things, there is an advantage. For example, Toshiba in Cambridge is working very actively with British Telecom in Martlesham—in fact, there is a fibre link between the two, to demonstrate secure communications between them. At this stage, companies are working together in consortia.

Q35 **Bill Grant:** At this stage.

Professor Knight: Eventually, one day, they are going to run.

Professor Delpy: The answer to the other part of your question is that, for the core of the national programme, it is the strategic advisory board. The strategic advisory board has all the partners on it, and in fact has worked extremely well and in a collegiate fashion. At the moment, the technical developments are pre-competitive. All the industries have a common interest in achieving a small-scale atomic clock or a small-scale gravity detector. Once those devices are available, each industry will decide where it wants to apply them, and then they will compete. At the moment, it is pre-competitive and has worked extremely well, through the strategic advisory board and through Peter in the challenge fund.

Bill Grant: That is fascinating.

Chair: We will take quick supplementaries from Vicky and Carol, and then go back to Vicky for her main question.

Q36 **Vicky Ford:** Imagine that I have a cheque for £338 million and I want to invest it in a transformative technology. I could invest it in next-generation batteries, AI, robotics or quantum. Why quantum, and why quantum in Britain?

Professor Delpy: Every one of the things you mentioned requires quantum. Quantum is an underpinning technology. Once it is engineered, it will be an underpinning engineering to all those things. You could invest in the automotive industry. The automotive industry will require a whole range of sensors that will be based on quantum phenomena, so my answer to you is that it is a core underpinning technology, in the same way as photonics, as a generic name, is a key underpinning technology. There are 1,500 companies in photonics. I would like there to be 1,500 companies in the quantum area.

Q37 **Vicky Ford:** Are you going to say there will be a quantum leap in the return on my investment, compared with the others? That is what I want you to say: the return we get from investing it there is multiples.

Professor Delpy: The evidence is that high-technology companies make a much greater return to the economy, in terms of efficiency and productivity, than others. The photonics industry has the evidence for that.

Q38 **Carol Monaghan:** It is good to hear photonics mentioned as part of this discussion. Following on from what Vicky was saying, we know that SMEs are quite heavily involved in the academic-industry links, but how involved are larger companies and industries? They are being asked to take on a risk in terms of future development that may or may not come to something. Is there an expectation of large-scale investment? Is it perhaps premature?

Professor Knight: There is an appetite to do this. When you talk to the large companies, as I have been doing for the past few months, many of them say, "We are not actually technology developers. We are technology acquirers." We want to make sure that there is a landscape out there developing new capabilities that are of relevance to them, which they will then invest in themselves. When we talk to the really big majors in this country, we find that there really is an appetite to do it. For example, in the end, one of the major investors will be BP, through acquisition as well as through co-investment.

Q39 **Carol Monaghan:** Aren't they waiting until somebody else is successful? Then they buy it out, rather than investing at the outset.

Professor Knight: No. It is almost like they have their own venture capital outfit. A lot of the big companies now have an investment strategy that is looking to invest in start-ups and innovation. Our discussion with the majors has indicated that there is an appetite for this. We want to see that grow.

You are right to say that, so far, the SMEs have been the most enthusiastic. They are also the ones that are growing rapidly. Some of the companies on the photonics side of what we do have been expanding at a tremendous rate, working on the new opportunities and hiring new people. For example, M Squared in Scotland, which you know about, and e2v, which Vicky knows about, are hiring a lot of new people, but they are still part of the supply chain. Getting it out into the BPs of this world is a challenge. British Telecom is on board, because it is an information carrier and knows that this is core to its business.

Q40 **Vicky Ford:** Before I start, I declare that Teledyne e2v is based in Chelmsford. My question is about commercialisation and how the next phase of the programme should support that. Are there problems with low industry awareness? You talked about that a bit in your answer to the previous question. What more should we do to address it?

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

Part of the campaign that we are running at the moment is to investigate ways in which we can overcome some of the specific issues. If you mention the word "quantum," it is kind of scary. We have four challenges in the current industrial strategy programme. They do not mention the quantum word; they talk about what it will enable you to do that you need and cannot get anywhere else at that cost and price. We really need to focus on the fact that we are building technologies and, just like many other acquirers of technology, you do not need to know what is inside the box. You want to know what it does that you want.

Professor Delpy: The other thing that we are doing is training people— particularly existing engineers in industry, rather than more PhDs—in what quantum can do for them. They do not need to know what the quantum phenomena are. As Peter said, what they need to know is what quantum can enable them to do that they cannot currently do. We have invested in three skills hubs to train existing engineers in what quantum can do for them. We already fund the CDTs, which have as their output skilled PhD students who then go into industry.

Q41 **Vicky Ford:** When you move on to the next stage and have your innovation centres, do you see them as being the same as or different from the hubs? Will they cover the same four areas? How do I differentiate the hub strategy and the innovation centre strategy? What is the difference?

Professor Delpy: They are very different. It should not be assumed that the innovation centres will be based at the hubs. The innovation centres are fulfilling a need that industry has for specialist facilities. Currently, the smaller companies may not have those. If the bigger companies have them, they do not have the time to invest in them.

They are specialist facilities. They will be a single place where industry can come to test some of the demonstrators that have already started to come out of the existing phase 1 programme. A disadvantage, to an extent, of consortia is that they are rather disseminated. The innovation centres will bring together in one place the industrial users—the people who have the application—the researchers who developed the original lab-scale proof-of-principle demonstrators and, ideally, the skilled workers who are coming through both the skills hubs and the CDTs. They will be physical centres that bring everybody together. The areas will be determined largely by what industry needs, rather than what each of the four hubs has as its prime academic interest.

Q42 **Vicky Ford:** Who do you expect to bid for them? You suggested that it would be industry.

Professor Knight: There are a number of opportunities for us. Looking at where the focal points of industry are, a lot of the laser industry in the UK is based in Scotland, around Glasgow. It would be foolish not to explore the appetite for something there. Bristol has a tremendously vibrant quantum culture at the moment.

Chair: You are making two members of the Committee very happy.

Professor Knight: They have raised £42 million—not from us; half is from industry—to build a quantum technology enterprise centre at Bristol Temple Meads. There are a number of others that are growing in this area.

Professor Delpy: To be honest, London, given the expertise at UCL and Imperial, would be another one to consider, but we are not prejudging any of them.

Vicky Ford: Essex is great as well.

Professor Knight: It is about where venture capital is as well. We know that we are going to end up with vision pieces from a number of people who say, "If you come here, we have tremendous opportunities for the UK economy." At that point, there has to be some serious thinking about the rival merits of this versus the other.

Q43 **Chair:** You do not expect that there will be any shortage of bidders.

Professor Knight: I think we will be overwhelmed by good ones. Possibly, we will have to start gluing some of them together.

Professor Delpy: Obviously, that will not happen until people know that the money has been committed for phase 2. One of the things we specifically said in the phase 2 bid was that the process would be very much one of building consortia again, but with a different focus for the innovation centres. It will not be a case of passively putting out a call and saying, "Here are the bids. We will decide between them." We, as part of the national programme, will look at the bids that are coming in, talk to Innovate UK and others, and then decide what mix would be the best, given limited money and the limited number of centres that we want to fund, rather than 17 nanotechnology centres.

Q44 **Vicky Ford:** If you are overwhelmed with good ones, let's make sure that we fund lots.

Professor Delpy: Yes. We need critical mass as well.

Professor Knight: You do not want a lot of sub-critical ones. We have learned from that.

Q45 **Vicky Ford:** Are the Government doing enough on demonstrator projects?

Professor Delpy: From the MOD side, DSTL has done a stunning job, as Peter said, both in testing and sorting out some of the risks involved and in funding real demonstrator programmes.

Q46 **Chair:** Does that suggest that there is a lack elsewhere?

Professor Knight: They were very quick off the mark.

Professor Delpy: DSTL was very quick off the mark. Again, we do not have large-scale system integrators or an industry. If we had a sector council, as there is in automotive, there would be a 20-year road map that would identify a series of demonstrators that we need, as Rolls-Royce has for 50 years. In this area, where we are developing an industry, we do not have road maps of the same precision. There are some key demonstrators that the defence area needed, and which had dual use. Increasingly, players such as BP, Airbus and others are identifying some key elements that they need and for which we will have to have demonstrators built in the innovation centres.

Professor Knight: There are two big MOD component parts. One is the quantum navigator. If you are working in a GPS-denied environment, how do you know where you are and where you are going? The other is the gravity imager, to work out what is in the substructure, where there is already an enormous civil appetite. The MOD thought that by investing in that, they would get an advantage, but they could derisk some of it. They built consortia with the best researchers and companies, so that the research groups could hand over the prototypes to higher TRLs in companies. That has worked very effectively. The MOD also funded 46 PhD students from day one of the programme. I led the peer review, where they said, "Get the youngest and the brightest—the really enthusiastic—and let's jump-start this." They were terrific on day one.

Q47 **Vicky Ford:** This is a question about governance and decision making going forward. A number of the people who submitted evidence to us said that, while UKRI has overarching help, it would be better to have some sort of quantum council or quantum technology executive board that brings together research and industry, to have that specialty within the governance structure, and that would have a more strategic view on investment choice that brings together industry, research and so on. Do you agree?

Professor Knight: That was one of the Blackett recommendations that Mark Walport and I put in. We wanted to make sure that our partners could be part of a common board, so that they could work out a strategic investment system whereby they could see alignment of where their money could go, compared with other people, in a common structure. One of the strengths of the UK programme is that we have all the stakeholders around the table in an advisory board. What we now want, with the opportunities that UKRI has, is to have an investment strategy with that common board.

Q48 **Vicky Ford:** You still need the specialism of the quantum board or quantum council.

Professor Knight: It would include industry—all the partners we want.

Professor Delpy: The board would be much more an executive than an advisory board in this instance. We would want it to decide on the allocation of the overall funding, to bring the integrated programme through. As I said right at the outset, in the existing phase, the money came quickly. We allocated the bulk of it via EPSRC and the rest through Innovate, because those were the only two mechanisms. The question is whether you have a board within Government or a special purpose vehicle—a bit like the Energy Technologies Institute—that is one step removed. I would prefer the latter, rather than its being embedded in Government.

Q49 **Stephen Metcalfe:** We have talked a little about the 2016 GO-Science report. There was a list of recommendations in that.

Professor Knight: So there was.

Q50 **Stephen Metcalfe:** How are we getting on with those?

Professor Knight: We have done pretty well on those things. Let me turn to my list. I believe that in every case progress is being made. It is 18 months since we finally parted company with it. There are some that will take a bit of time. For example, recommendation 2 was on "critical services dependent on GNSS." As you possibly know, that produced some headaches for us around Galileo. I believe you have had a little poke at Galileo recently.

Q51 **Stephen Metcalfe:** And will be continuing to do so.

Professor Knight: What we did was produce yet another Blackett report, on GNSS. As a result of that, the Cabinet Office, through civil contingencies, has set up an implementation group that involves all Government stakeholders to worry about that. I am a member of it.

That is an example. Basically, it is all ticking over. The GNSS one will require more work, given the kerfuffle about Galileo. For the others, we have put in place structures to implement some things—on standards, National Cyber Security Centre engagement and so on. I think it is all working fine. There is one that causes me some concern, and we are dependent on your assistance on that. It is recommendation 1, on the continuation of the funding. Mark and I wrote the report, with assistance from a lot of others. We have used the two years, roughly, since we started to make sure that we have put in place mechanisms to deliver on each of the recommendations.

Professor Delpy: In fact, the SAB has responded to Mark on each of them. The things we could not move quickly on are built into the phase 2 bid. They are addressed very clearly in that bid.

Q52 **Stephen Metcalfe:** Very good. On the red-amber-green basis, there is only one red, and there are a few ambers and a couple of greens.

Professor Knight: There are a number of greens where we can really celebrate. An indicator of the fact that our instincts are right is the appetite for other nations to emulate what we are doing. The United States is spending a great deal more per annum on quantum technology than we are, but it is fragmented among many rival organisations. The bid that went to Congress from the national photonics alliance quoted what we did and said, "We've got to pull these threads together," but I see no appetite whatsoever for the agencies to collaborate in the US. It is extraordinary.

Elsewhere, there is an initiative called Quantum Canada, which has been trying to emulate what we do. The Singaporeans are looking very closely at what we are doing. The European Union flagship, with the pillars it will focus on, is more or less a clone of our programme. Our instincts five years ago about what was important are proving to be right.

Q53 **Stephen Metcalfe:** Excellent. To continue to make progress, you said that you need more funding. Presumably, the innovation centres are completely dependent on that funding coming through.

Professor Delpy: Yes.

Q54 **Stephen Metcalfe:** If it does not come through, what will happen?

Professor Delpy: I know a lot about EPSRC. In the absence of a firm decision, its council decided that it had to ensure that the quantum activities were continued, so it has put in place a process for the renewal of the hubs. That is predominantly the academic part of the hubs, of course. Innovate is working closely with the EPSRC, but, obviously, it needs to know what budget size it is likely to have. EPSRC has possibly a greater degree of confidence in its budget going forward. The process for the renewal of the hubs has started, but the innovation centres, which are a key component of phase 2, will really depend on additional funding coming in. It should be routed through Innovate UK, because the centres are driven by the needs of industry, not the academic base.

Professor Knight: But we have the ability to refresh the academic base as well.

Professor Delpy: We have to.

Professor Knight: A number of new groups have been merged, with new leadership, in the five years since we started. We need to find a mechanism for acquiring those new people, with new insights, and getting them to come on board, to keep the critical mass of new ideas going. As part of the hub refresh, the hub directors are tasked with looking at ways in which we can bring on board the new groups that have come into existence since we started five years ago.

Q55 **Stephen Metcalfe:** There is a lot of work and activity in this area that is progressing quite quickly and expanding. Is it in need of any form of regulation yet? If not, great; if so, what might that regulation look like, and have any of those discussions started yet?

Professor Delpy: It depends on what you mean by regulation. As we proposed, there should be an executive board to manage the second phase of the programme in a more coherent way. There is a lot of work on the regulatory side of quantum sensing through NPL and now with the advanced Quantum Metrology Institute. That is embedded in all the quantum activities.

What came out of the public dialogue was that the public wanted to ensure that the developments that occurred were used to the benefit of all. What they were really interested in was, first, whether the developments would disappear from the UK and go elsewhere—they did not want that to happen—and, secondly, whether the developments would be accessible to all areas of society. They identified healthcare areas rather than just the defence and security side.

Q56 **Stephen Metcalfe:** If it is involved in healthcare, does that mean that it is not a matter of regulation but perhaps standards?

Professor Knight: That is different. Appropriate standards and a bit of a light touch are absolutely essential. Inappropriate standards, or a heavy-handed attitude, could seriously cripple an emerging technology. For example, in healthcare one of our deliverables in the programme is to work out whether we can build a brain imager the size of a football helmet, not one of those damn great scanners, with better resolution and not so scary. There are considerable constraints on the operation of new technology in the healthcare industry, so early dialogue on appropriate standards is essential to roll it out.

Q57 **Stephen Metcalfe:** Have the lines of communication between standards bodies and regulators been opened?

Professor Delpy: Yes.

Professor Knight: Yes. NPL has been talking a lot with the British Standards Institute. We are also talking with others in this area. We have talked to Government Departments that also have an interest; we have talked to DIT. Yes is the answer.

Q58 **Stephen Metcalfe:** One of the recommendations in the GO-Science report was for a new body with the "funding and sole remit to co-ordinate activities across the programme." Does that role still need to be filled by UKRI taking it up, or is there an alternative that you put forward?

Professor Knight: That was what we thought about the executive board.

Q59 **Darren Jones:** I have two questions on international collaboration and a final one on our report. No one has mentioned the B word yet. There seem to be potential opportunities and risks if Brexit happens. We have already talked about the EU quantum technology flagship, and the Committee has done some work on FP9 and Horizon Europe. I would be interested in your views on that and, if Brexit happens, whether you think there are opportunities for deviation that would give us competitive advantage in this space.

Professor Knight: It is important to put the flagship into perspective. It is €1 billion over 10 years. Half of it will come from central funding; for the other half, there is some ambiguity about industry versus rolling in national programmes. Let us assume it is €500 million and we play a full part in all of it. Given the size of our community, we would expect our share, based on past participation, to be of the order of between €6 million and €7 million per annum. We are spending €100 million on the national programme. It is nice to have. It is not the main driver of our programme, but it is an essential component by which we engage with the brightest around Europe, and we have benefited enormously from it in the past.

Q60 **Chair:** In a way, it is collaboration more than the money.

Professor Knight: Money is the lubricator of engagement with the cleverest.

Chair: Well put.

Q61 **Darren Jones:** Are there any opportunities?

Professor Knight: We believe there is an opportunity to form bilateral engagements with countries with a similar attitude to ours and matching capabilities. I led a UK mission to look at potential collaboration with Canada where there is an appetite for a number of things at this very early stage, including quantum entrepreneurship training and so on. It is a matter of looking at bilateral opportunities with a modest amount of money that could lubricate engagement with some of the countries where we have traditional and historical science and technology links.

Canada has a very similar ecosystem to ours, Australia has a very similar interest and Singapore has lots of strengths. We are looking at bilateral engagements of that kind. There is an opportunity. It does not require an enormous amount of funding—merely some flexibility to encourage consortia to be formed.

Q62 **Darren Jones:** You mentioned earlier the European Telecommunications Standards Institute. Is that a function of the European Union, or is it separate?

Professor Knight: It is separate.

Q63 **Darren Jones:** So it should not be an issue around Brexit.

Professor Knight: Leading elements in that ETSI working group are at Waterloo in Canada, by the way.

Q64 **Darren Jones:** My next question is about non-EU international collaboration. I understand there have been some challenges around dual use of the technologies between defence and commercial applications, and the US takes a particularly restrictive view on the use of defence in commercial areas. Linked to that, for us lot in the UK, I think we are saying that the hubs and innovation centres are the places to go to try to figure out dual-use restrictions and challenges. Do you think that is the best answer to help the process?

Professor Delpy: I think the answer is yes. There are always problems, and industries that work in those dual-use areas are fully aware of the ITAR rules and regulations. The academic community in general has not been aware of that, but SAB has, particularly with the help of DSTL. Quite early on, when we were approached by lots of countries, including the American Department of Defense, DSTL with SAB produced an ITAR spreadsheet and document for all the academics and ran workshops, just to identify for academics the potential hazards and where one can easily continue real academic dialogue and work, but avoid the potential risks of ITAR in particular.

We have done quite a lot to try to ensure that each of the hubs is aware of the potential downsides, but the upsides of collaborating with great researchers in the US are very significant, and we have to be sure we do not put them off from working with us.

Professor Knight: We need more clarity on ITAR. There is a fear of ITAR, which is an inhibitor, and we need more clarity on the reality of ITAR.

Q65 **Darren Jones:** Presumably, that is a greater risk as we move into the commercialisation phase, as opposed to the research phase.

Professor Knight: Precisely.

Professor Delpy: Yes, but at that point it becomes something that the companies involved will be very aware of and they will manage their academic collaborations in such a way as to avoid it, hopefully.

Professor Knight: Some of the technology developments they are worried about concern what is called ITAR contamination, where they acquire a US presence within the programme. It may be just manpower for a year—the Americans are very good at that—and that may put some constraints on them. The fear is almost certainly greater than the reality. We are working on clarifying it.

Q66 **Darren Jones:** It has been suggested that some of the concerns about US collaboration, and certainly the contamination questions—we see quite a lot of that already in the defence industry, with the procurement of fighter jets and so on—mean we end up working with other countries, China perhaps, as opposed to the US. Do you, or any of the organisations you work with, have any fears about national security, IP or other issues around that move, as a consequence of the concern about the US framework?

Professor Knight: We have an awareness of the area.

Q67 **Darren Jones:** That is a very diplomatic answer. I will move on to my last question.

We have heard loud and clear that you want us to make a recommendation for the autumn Budget, so well done for getting that point across. We would like to make more than one recommendation. If you were holding the pen, what would be the second and third top priorities for you?

Professor Delpy: Assuming the funding is there, it would be nice to see very strong support for the innovation centres. It would also be nice to see some comment about the overall governance of the future programme. I have already put my cards on the table. I think we need a high-level executive board, possibly even a director, but I would not want to see that embedded in Government. The whole advantage of this programme is that it is a mix of industry, academia, Government Departments and other institutions that have worked extremely well together. They have found a way of working and it would be nice to keep it outside, rather than embedding it within UKRI, BEIS or some other Government Department. There should be some comment on governance.

Q68 **Darren Jones:** Is there a third one beyond money and governance?

Chair: Professor Delpy said focus on innovation centres as well.

Professor Delpy: Yes. My third one, wearing my old EPSRC hat, would be a proposed increase in funding for the research councils, because, if you are growing a new technology, you need further basic science work all the time to solve the problems that the engineering and technology development have brought up. If we grow one thing, the consequence is that the poor old research councils see growth in that area, so what do they then shrink? We should grow the basic science, and in particular probably the training. The skills are the key.

Professor Knight: I was going to emphasise skills. We will suffer if we do not have a supply chain of suitably qualified and experienced people. We are trying to create a new discipline of quantum engineers. When we start to produce the products that we know are in the pipeline, where are we going to get quantum apprentices from? We are working on a whole raft of things at the moment, so skills enhancement is hugely important.

Q69 **Chair:** Presumably, that means growing our own, but ensuring that we can still get access to the best people around the world, including the EU.

Professor Knight: Exactly.

Professor Delpy: Yes.

Q70 **Stephen Metcalfe:** To go back to the overall funding level for research, are you saying we need to accelerate the road map towards 3% of GDP?

Professor Delpy: I will always say that. At the moment, there is specific short-term growth in underpinning basic science in quantum areas, and there is no increase in the overall budget for the underpinning of science from the research councils.

Professor Knight: We mentioned the European Union. There was something I meant to flag up and forgot, so I will now if I can have five seconds. The European Research Council has been extraordinarily effective in underpinning the long-term ambitions of the best of our scientists in this field. We are driven a lot in our technology programme by making sure we have an impact on the economy, but underneath it all we have to give people time to think of the big picture over a long period. The ERC awards are critically important to get some of our people funded.

Q71 **Chair:** What is the sort of timeframe?

Professor Knight: It is of the order of five years. Equally, the university research fellowships of the Royal Society are eight years. An awful lot of our quantum science has been propelled by young people who got those sorts of fellowships and created this new field. We have an opportunity to enhance the ability to underpin through the URFs, but the ERC is really important.

Q72 **Chair:** Continued participation for you is very important.

Professor Knight: Yes, because it underpins things in the longer term.

Q73 **Vicky Ford:** Can you just replace the ERC with more Royal Society fellowships?

Professor Knight: We are conflicted. Both of us chair URF committees at the Royal Society.

Q74 **Vicky Ford:** It is really important that you give us that clear statement. Or do they do a different job?

Professor Delpy: They do a different job, and they are perceived differently.

Q75 **Vicky Ford:** That is enough.

Professor Knight: But they are great and they have created this field.

Chair: Thank you both very much indeed. It has been an absolutely fascinating session.

Examination of witnesses

Witnesses: Jonathan Flint, Professor Pepper, Professor Morton and Dr Montanaro.

Q76 **Chair:** Welcome, all of you. We have overrun with a panel of two, and now we have a panel of four, so it is quite a challenge. My plea to you all is to be disciplined, with tight answers, and not to feel you all have to answer every question. If you feel you have something to add, please do so. Can we have quick introductions?

Professor Morton: I am John Morton, professor of nanoelectronics at University College London. I am also a director of UCLQ, which is UCL'S Quantum Science and Technology Institute, and a co-founder of three start-ups in quantum technology.

Dr Montanaro: I am Ashley Montanaro. I am a lecturer in applied mathematics at the University of Bristol. I am also a co-founder of a quantum software start-up Phasecraft. I am here on behalf of a group of UK academics working on the theory of quantum computing and quantum information.

Professor Pepper: I am Michael Pepper. I am Pender professor of nanoelectronics at UCL, emeritus professor of physics at Cambridge and fellow of Trinity College and a visiting professor at Oxford. I was the founding managing director of Toshiba Research

Cambridge. I am now senior adviser to the company that, as you know, is commercialising quantum cryptography. I am co-founder and director of TeraView, a start-up company commercialising terahertz technology, which is the region of the spectrum between infrared and microwaves.

Jonathan Flint: I am Jonathan Flint. I am a physicist by training but have spent my career in high-tech industry, aerospace. Most notably, I was chief executive of Oxford Instruments, a FTSE 250 company specialising in high technology, particularly nanotechnology, as a tool provider for the emergent quantum industries. I am now non-executive director of a number of businesses, including Oxford University Innovation, which spins out small companies from Oxford University. I am on the QuantIC advisory board for one of the themes in the national quantum programme, and I am here as president-elect of the Institute of Physics.

Q77 **Chair:** Thank you very much. My first question is to Jonathan and Sir Michael. What opportunity do you see for quantum technologies overall, and what priority do you think Government should place on them in comparison with other technology sectors?

Professor Pepper: I am representing the academy, which is of the view that it is an extremely important technology. Parts of it have the potential to become revolutionary, particularly quantum computation and quantum cryptography; others will produce an improvement in existing products. We believe it should be a very high priority.

The next phase should certainly be industry led, and we see the important role of Innovate UK. At the same time, we are concerned that less attention may be paid to basic research in universities developing new quantum processes and laws. We see this not as a short-term development proposal but as something that will be long term. For example, consumer electronics has been used as an analogy. Although the transistor was invented in 1948, the silicon chip was invented in the 1960s; it has been evolving over 50 years. We see that as the likely outcome for quantum effects, so we must not think of this as a short-term endeavour.

Jonathan Flint: I agree with what Professor Pepper said. It is a uniquely broad endeavour, and wider than other things I have been involved in. When I was leading Oxford Instruments, we based the business strategy on this opportunity. That unique broadness also brings with it some difficulties. It is quite difficult for anyone to define uniquely how big the market is. We are in a pre-market position.

The products, competitors and industrial landscape are not yet defined, so no one can rightly say this will be worth £100 billion or whatever in X years. However, it will be an underpinning technology for a variety of products and other industries, and it should not be considered in isolation. Today, it is a foundation for next generation industry across a broad range of possible applications.

Q78 **Chair:** In part, you have possibly answered the next question I was going to put. The Government Office for Science estimated in 2016 that quantum technologies could grow to become comparable with the consumer electronics sector that you mentioned, and worth £240 billion a year worldwide. Is that a reasonable estimate, or is it just impossible to make that judgment?

Professor Pepper: It is very difficult to say. What one can say is that consumer electronics in its early stages was the development of the silicon technology, as we know, and that was driven by military and space spending. It was very expensive, and the military had to have it, mainly to go into rockets and for the space programme, because it was replacing glass valves that would break. It was that which drove it, and as the applications became clear, and the technology became cheaper and more widespread, it spread into consumer electronics, but in the early days it was just transistor radios.

Professor Morton: I agree it is difficult to put a precise number on it, but if you look at the fundamentals of what quantum technologies offer, you can see how that could impact something like consumer electronics. Quantum computers offer a profound change in computing capability, and computer processing underpins not only consumer electronics but much wider fields. Security is a growing concern in consumer electronics—the data you share with Facebook etc. Quantum communication offers fundamental ways to solve problems in security that are not available through classical means, and sensors—as Sir Michael mentioned—can be enhanced also. In each of the areas where there are currently very large market values, quantum technologies offer profound changes.

Q79 **Chair:** Is it just quantum computers and computing that promise the revolutionary capabilities? Is that the big prize we are focused on?

Professor Pepper: That is certainly the greatest attraction. It relies upon new developments in quantum physics and a very difficult technology, so it is the greatest challenge. Quantum cryptography is here and now; basically, the systems are being trialled and they will go into appropriate use in the next two to three years, but that has taken a very long time. We first developed the underlying physics back in 2001-02, and in 2018 it is entering the post-development phase. It is advisable not to underrate the amount of time and effort it takes to bring these technologies to market, but it is more or less at that stage now.

Professor Morton: Reference was made earlier to the coherence of quantum technologies, the common underpinning ideas that give them their power, and the common skills and training needed to develop them. It is also important to recognise that they represent a diverse set of applications operating on a range of timescales. It is important to have the high-risk but highest-reward technologies such as quantum computing as a core part of the programme, but to recognise that quantum sensors and quantum communication offer the ability to start to put products out there. Together, they can form part of a coherent programme.

Jonathan Flint: I agree. Quantum computing is rightly the poster child for quantum technologies at the moment and the implications are huge, but I would not dismiss the rest of quantum applications yet, because it is very early on. In QuantIC, we are involved with a camera that can see round corners; it can look at things that it is actually not looking at. It is quite profound and counter-intuitive. Just think through the possible applications for security and privacy of a technology like that. The quantum world is riddled with those sorts of applications, which could come out of the highly counter-intuitive nature of quantum mechanics.

Q80 **Chair:** Could you deal a little more with how close quantum technologies are to market? Are they sufficiently advanced for Government procurement, or Government-supported demonstrator projects?

Professor Morton: There are different answers for different types of quantum technologies. Quantum sensors are already being commercialised, and are ripe for procurement by Government or indeed other customers. Quantum communication is nearly there. A demonstrator has been put in place. That looks as if it is in the right timescale.

On quantum computing, the timescales have definitely shortened compared with what we thought about at the beginning of the previous phase. We expect this year a quantum computer to be able to solve a problem that the world's fastest super-computer cannot solve. It will not be a useful one, and we expect it to stimulate a lot of work over the next, say, three years to find useful problems that such computers can solve. Even in quantum computing, we can imagine that over the course of the next phase of the programme there will be some development.

Q81 **Chair:** There is an acceleration of the discovery.

Professor Morton: Absolutely.

Dr Montanaro: I agree. There are companies that now have available relatively small-scale quantum computers of the order of, say, 20 qubits—quantum bits. You can already access them through the cloud. Within a year or so, systems of 50 or 70 qubits—that sort of range—will be available. They are still relatively small, but within the next few years it is quite plausible that there will be larger-scale systems that might be worth considering from a procurement point of view.

Q82 **Chair:** Are there any specific demonstrator projects that the Government should be pursuing? We have heard that defence has been the area where this has developed, but perhaps other areas are behind on that. Where should the Government be focusing their attention?

Dr Montanaro: Within the computing space, which I will try to focus on, a recommendation in the Blackett review of 2016 was for Government to work on challenges in quantum computing, essentially applications for quantum computers and figuring out things they can do.

A very important aspect of producing a demonstrator is: what is the most important challenge for that demonstrator to solve? That is most usefully addressed in an integrated approach where people are working all the way through, from the fundamental science right through to the physical technology. In the coming few years, demonstrator applications to do with problems in the pharmaceuticals industry, energy industry and so on, are important ones for Government to consider.

Q83 **Bill Grant:** How successful do you feel the first phase of the national quantum technologies programme has been? Does anyone believe that maybe a major element has been under-supported or left behind in the current programme?

Professor Pepper: There is some concern about the funding of basic research, because success rates are quite low now; but, broadly speaking, the hubs have fulfilled their purpose and the international review was fairly satisfactory.

Professor Morton: We would be of the view that quantum computing, given the potential impact, has perhaps been under-represented. In particular, it is important to recognise that we are at the phase where different platform technologies are being explored for quantum computing; there are different ways to build a quantum computer. As the applications develop for quantum computers, quantum software should be strengthened going forward.

It is important to recognise that we should look at the hardware platforms in quantum computers that have the most promise and take-up by wider industry, and not be afraid to invest in those areas because major internationals and other companies have bet on that way forward. It is important to recognise the value of being part of a successful product or a successful platform, and not invest in something niche for the sake of avoiding what the rest of the world is going for. Perhaps there should be a broader approach to quantum hardware development, and quantum computing and quantum software.

Jonathan Flint: Broadly speaking, I agree. The current programme covers the main bases very well. I have been involved in a lot of academic and industrial collaboration programmes in my career. The quantum programme is one of the best; it is certainly the most productive I have been involved with.

I agree that we have not emphasised quantum computers as much as we might have done in the UK, and I understand the reason for that is that other people have already made significant advances. For example, in Oxford Instruments, we were already making sales of over $1 million a year to a Canadian company that claims to be producing a quantum computer and is selling them for tens of millions of dollars at the moment. There is much academic debate about whether that programme will eventually work, or indeed whether it is actually a quantum computer at all in the first place. There are many different varieties and flavours of quantum computer, and just because someone else has lots of money to do something elsewhere in the world does not mean we should not have a good foundation in the UK for the many other technologies that could be equally lucrative.

Dr Montanaro: From our perspective, the quantum technologies programme has been a really impressive achievement in the development of quantum hardware and in associated innovation activities too. An aspect that we think is under-represented is the software side, which John has already briefly mentioned. Ultimately, if you do not have the software, you cannot use the hardware. In particular, you need to do the research on the software side now, to be ready for the large-scale quantum computers that we will have in a few years' time, and to figure out how best to use the small-scale ones we have now.

I completely agree about the importance of fundamental research, which in this field in particular, but in many other aspects of science, has been completely critical. One example is the theory of quantum teleportation developed in the early '90s, in 1993. It took a few years for it to be developed experimentally. Now it is so routine that you can log into IBM's quantum computer on their website and do it yourself, using their machine. That is the kind of lead time we are seeing from theoretical ideas to technology, which is why we think it is very important to fund that kind of activity now.

Q84 **Bill Grant:** On the same theme, should there be co-location of hardware and software hubs? I believe they are integrated, or they work together. Should they be separate hubs, or is it absolutely essential that they are together?

Professor Morton: It is most important that there is very strong integration. Especially in the first phase, we expect the software to be designed around early-stage hardware. It will not be abstract for a perfect quantum computer; it will be tailored to the hardware that exists, but it is important that that is done within the framework of a broad enough hardware effort so that we are not writing software just for one particular type of quantum computer we are trying to build and which is not relevant for a wider set of platforms.

Equally, we have to build quantum hardware that has applications and software that have been fully worked through, which is ultimately what will connect the hardware to the end user. Integration is key, whether that is done through co-location or indeed through other mechanisms. There are other ways to integrate closely instead of co-location, but doing that across multiple quantum computing hardware platforms will be important.

Dr Montanaro: From our perspective, it is important that software is recognised as having its separate nature in some sense. I completely agree with John that close collaboration and communication with the hardware is very important, especially at this early stage, but a key feature of software is that it is independent of hardware. You may have many different hardware platforms, but software based on similar ideas could run on all of them.

In the long run, it is not so clear whether or not the UK will be manufacturing a particular kind of quantum hardware. If we look at the history of standard computers, the UK is not a major manufacturer in many of those technologies. On the other hand, we could be a leader in software without necessarily having the hardware in the UK too. Although software is closely linked to hardware, it is a separate entity.

Professor Pepper: Software is an area of major expertise in the country. I think everybody here is familiar with the fact that UK industrial history is full of technologies that were wonderful but never made it to the market because they were not designed with the customer in mind. We feel that the next phase of this exercise should be industrially driven, and should bear in mind customer requirements, which we find to be the most important factor in determining the future of the programme.

Q85 **Vicky Ford:** How do you do that? How do you get people to choose industry-driven investment?

Professor Pepper: Do you know the story of how the Japanese computer industry got going back in the days when laptops were first coming out? Essentially, a Government agency bought 5,000 from the major manufacturers and then sold them to retailers. When the retailers sold them all, they ordered more, so the Government agency ordered them from the manufacturer. In that way, the manufacturer that produced the most customer-friendly device prospered and the others did not. One cannot do that with quantum computation and quantum cryptography systems, but there is no reason why Government should not purchase several examples of those products, use them in principle and then select the best performers.

Q86 **Bill Grant:** Does anyone sense any bureaucratic challenges when dealing with Innovate UK that may delay the start of projects, or is it harmonious?

Professor Pepper: We have had quite a lot of experience with Innovate UK in the terahertz region of the spectrum. It is quantum but not part of the quantum initiative. We have been very satisfied with the response we have had and the time they take to consider applications.

Professor Morton: There is no particular criticism about the bureaucracy, but it is important to recognise, particularly with something like quantum computing, that projects tend to be long and ambitious, with industry and academia working together, and the 12-month timescale of many projects prohibits looking at some of the more ambitious challenges. It is important that within any joint academic and industry-led projects there is a timeline to work on more ambitious projects.

Q87 **Bill Grant:** We should reduce the timeline.

Professor Morton: No, we should increase it beyond 12 months.

Dr Montanaro: I am currently involved in Innovate UK projects working with BT and other industrial partners to look at applications of quantum computing in the telecommunications industry. This has been very valuable. Although we experience some kinds of minor bureaucratic issues to do with delays in starting the project and so on, I cannot say that has affected us very significantly. It has been very valuable; nevertheless I agree that longer-term projects would be quite welcome.

Q88 **Bill Grant:** There seems to be general agreement on that.

Looking at the next phase of the national programme, is it wise simply to build on the first phase and move on with that, or should it be tweaked or done differently? Is there something you would add? What would you change about the first as you go into the second?

Professor Morton: The field has changed dramatically from five years ago, when the first programme would have been in its design phase. There are now huge changes in the balance between academic and industry-led research. Today, the most advanced quantum processes are in industry labs, not university labs. The same was not true five years ago.

There are changes in the way technologies are leading. There has been a huge growth in start-ups around the world and in the UK, with different quantum technologies. There has been a more than fivefold increase in the number of start-ups. Five years ago, you could probably count on one hand the number of quantum computing start-ups; now it is probably approaching 30 around the world.

Q89 **Chair:** Are you saying this means that the second phase needs to be different?

Professor Morton: It needs to recognise the dramatically changed landscape, and be designed according to the new opportunities, the landscape of players and the leading technologies today, rather than five years ago.

Q90 **Bill Grant:** In your written evidence, you argue against automatically maintaining the number and focus of the hubs in the next phase. What changes and what direction of change would you like to see?

Professor Morton: Recognising that changing landscape, there are some technologies that have been well developed through the hub process and brought through to commercialisation, and it is clear that they need to go out of the door and move on to the next phase.

Q91 **Bill Grant:** They are flying; they are off.

Professor Morton: They should be. There are other technologies, particularly around quantum computing, which were viewed as quite early stage five years ago, with large uncertainties as to when or whether they would come to fruition. Now it is much clearer where quantum computing is heading and what the scale of approach is, and that there is an appetite from industry, both established and small scale, so it is about making sure that those aspects of quantum computing and those platforms form part of the programme.

You almost need a two-track approach. It is not going to be one shape of entity, like a hub, for each quantum technology. You need to recognise the diversity among quantum technologies and have different structures to accelerate them.

Q92 **Bill Grant:** Are there any alternative views?

Dr Montanaro: I agree. Even within quantum computing there is a dual sense in which support is needed. There are things that are long term where we are looking at a five to 10–year horizon to get into industry and be genuinely useful to the consumer, but there are also things that are much nearer term, using and developing the near-term devices that we have now and will have in the next couple of years. On that side, it is very important to maintain support, along the lines of the Innovate UK programmes, to work with industry to understand the needs of end users and develop applications for them, and to work with the quantum hardware providers to write applications for them to develop their own architectures. It needs dual-type support for quantum computing.

Professor Pepper: Whatever the outlook, the thing to bear in mind is maximum flexibility. That is incredibly important. One has to sit down and say, "What are the advantages of the academic group and what are the advantages of the industrial group?" because their talents lie in different directions. We should then try to put the best together but not have any competitiveness between them. That is quite an important framework to lay down, regardless of the technology being pursued.

Jonathan Flint: The difference I would like to see is as rapid as possible migration towards industrial involvement in these technologies for the ones that are mature, while we go on supporting in an academic way those that are still some way from market.

Q93 **Bill Grant:** It is finding what the marketplace needs or wants.

Jonathan Flint: Yes. Industry has a role to play in bringing near-to-market products into real products.

Q94 **Bill Grant:** To jump the final hurdle and put them into the marketplace and be a commercial success.

Jonathan Flint: Yes. I would like to see more industrial involvement in the programmes that are ready, at that stage of maturity.

Professor Pepper: The requirement for matched funding that one sees in many of the document submissions is a major disincentive. Matched funding can be quite laborious at times. If they are expensive projects, and the return is some time away, matched funding could be very difficult.

Q95 **Bill Grant:** Is that a suggestion for more Government support to reduce the amount of matched funding?

Professor Pepper: Basically, it is about how you go about costing the projects and what you do about the overhead elements—the buildings, depreciation and that sort of thing—to make it financially more attractive for companies to come in with a financial contribution.

Q96 **Chair:** Matched funding may be unrealistic in some circumstances.

Professor Pepper: It could well be. My personal experience was back in the early days of quantum with GEC and BT. GEC was a major force in electronics. Basically, we could never get more than 20% matched in the first four years, and then it dropped out.

Q97 **Carol Monaghan:** We know that the UK has academic strength in quantum. Is quantum unique in the challenges it faces in terms of commercialisation?

Jonathan Flint: I do not think it is fundamentally different from other new technologies as they emerge. The difference is that it is very broad-reaching and touches a number of existing technologies and markets. It is not one thing. We are not inventing a new widget; we are inventing a new way of using science to make products and make wealth. That is unique to quantum.

Q98 **Carol Monaghan:** Do you think that is understood by those who could exploit the technology?

Jonathan Flint: In some cases, yes. The further you get from the academic centre of this technology, the less that understanding is pervasive. The man in the street probably could not name the way quantum technology could change his life. It is understood in the board rooms of some tech companies. Certainly, the big US companies have quite heavy investments in this area, which they are keeping proprietary within the commercial boundaries. Smaller businesses further away from high-tech would have lesser understanding.

It touches very many things. We have talked about photonics. That is one discipline. There are all sorts of others from an engineering point of view, such as cryogenics, which touch this. They are all part of the toolset necessary for a vibrant quantum engineering base in this country.

Q99 **Carol Monaghan:** Professor Morton, it appears that at the moment there is fairly good collaboration between industry and academia. I had the pleasure of visiting the QuantIC hub in Glasgow, which is quite an impressive set-up, but I do not fully understand how the national programme's proposed innovation centres would differ from the hubs. I know it has been touched on, but maybe you could expand on that a little.

Professor Morton: Different people have different ideas about what types of innovation centres we should be looking at. The hubs have been very much university focused, with some industrial partners providing input, some funding, guidance on strategic directions and some access to facilities. I view the innovation centres much more as places where businesses, seconded staff from big industry and start-ups come together and form the beating heart of the innovation centre, with input from academic staff.

Q100 **Carol Monaghan:** It is driven by industry.

Professor Morton: Indeed. It is quite a different purpose. It is the location where start-ups are based, and the location where a company that decides to create a team focused on quantum technology can base it, and interact with those developing the technology. In that sense, it is a profoundly different role from the one the hubs are playing.

It is important to note, therefore, that different innovation centres should have different focuses. Quantum technologies are diverse, so to form that melting pot they need to pick different application areas to bring people around. They will also need some type of infrastructure in many cases. It is not just office space or prototyping space. For example, in quantum computing some of the leading approaches require ultra-cold measurement apparatus that is costly and takes time for any industry to get going, whether it is a start–up or an established industry.

We have set up a facility at UCL precisely to cater for that kind of industrial need. Industry can come and use certain facilities, and help get their own R&D projects going much more quickly. That is an example of the kind of infrastructure that innovation centres could have to help that process.

Q101 **Carol Monaghan:** That gives us a clearer idea. You mentioned "they." Who is that? Is it UKRI, academia or the industries themselves? Who will decide to set this up?

Professor Morton: The idea of vision pieces was raised by the previous panel. Probably the right way to do it is from the ground up, having the people who wish to run the centres provide their visions for the theme they should have and how they would run them, and then people would put forward what they would like to set up with partners.

Q102 **Carol Monaghan:** Sir Michael, the royal academy's submission told us that more collaboration was needed to improve manufacturability, reproducibility and validation of quantum technologies. What sort of collaboration are you suggesting or do you envisage?

Professor Pepper: The involvement of companies and potential customers at an early stage, not so much at the basic research stage but when effects have been found and there is an opportunity to design systems or devices based around them. At that stage, customers and companies should be brought in to ensure that they meet the requirements of both standards and usability.

It is quite straightforward to have a complex system that works in a research lab with an army of PhDs manipulating it, but, if you want to put it into a factory environment, essentially you just want red light, green light—go or no go. That particular conversion can be a major step, certainly in the drug discovery area, which is different from this. Nevertheless, the lessons are still appropriate. There are many cases where new drugs are formulated and produced on a small scale in the research lab but never make it because it is impossible to manufacture them on a large scale. That is what we want to avoid.

Q103 **Carol Monaghan:** That helps. Some of the submissions we had talk about the value that academics are placing on intellectual property. Is there sufficient motivation for academics to commercialise their research, or should UKRI be shifting the academic focus from papers to patents in this particular area?

Professor Pepper: There is always pressure in the university sector to take up patents and valuable intellectual property. The universities have departments that cater for that. People from those departments come to give talks to scientists, particularly the younger ones at PhD and post-PhD level, about the importance of taking out patents where appropriate.

The process has now been speeded up, so it is possible that the time between sitting down with somebody and filing a patent can be as short as 10 days or so. Previously, it was thought, "This will hold up our important publication. We need to get an abstract in for a conference," and that sort of thing. That is no longer appropriate. It is quite straightforward.

Q104 **Carol Monaghan:** You believe that UKRI is taking good enough notice of patents as well as papers.

Professor Pepper: Basically, yes. In the research assessment exercise, or whatever it is going to be called next time, patents will be there, to give credit to institutions.

Jonathan Flint: In my involvement with Oxford University Innovation, we have a long stream of academics looking to commercialise their ideas. I do not see them as ivory tower people.

Q105 **Chair:** There is plenty of appetite for it.

Jonathan Flint: Exactly. We have to turn them away and say, "There's no market for this," or "You haven't got funding for that." That is well understood by most technical academics. While papers may be a UKRI-metric, if you are looking for industrial sponsorship—much applied research has a great deal of industrial money—they will look for patents, and that provides an added incentive for academics to get those in place early.

Dr Montanaro: As a previous speaker said, there is already a lot of incentive for academics to get involved in innovation activities and commercialisation. What they do not necessarily have is the capacity to do so. At the moment, there are relatively few people working in academia in quantum technologies, in particular quantum computing and the software side of things, and they do not necessarily have the time to get involved in all the activities they would like to do, so for me at the moment that is a bigger issue.

Chair: Vicky, do you want to ask questions on Brexit now if you need to go?

Q106 **Vicky Ford:** I was going to ask a series of questions on Brexit but I also have to go to the Chamber, so I will jump in. What are the main opportunities and risks that arise from Brexit for the development of quantum technologies? How important is it to be involved in the quantum technology flagship programme, where I know the UK has played a leadership role?

Professor Morton: In terms of involvement with the quantum flagship, I fully concur with the answer given earlier. The level of funding is nice, but the biggest advantage for the UK is the connection with European science and facilities. My students can hop on a train and be working in a collaborator's lab in Paris in three hours. That is unique to Europe, so there is a geographic element. The facilities in France and Belgium that we use to fabricate and test quantum chips are used by Intel and Samsung. They come to those facilities to run those tests, so it is important that we recognise that the facilities are on our doorstep and work with them. Beyond Europe, clearly there is scope.

Q107 **Vicky Ford:** Just Europe first, and then we'll do beyond Europe.

Professor Pepper: More generally, in my industrial capacity with TeraView and terahertz technology, I used to be approached maybe six or seven times a year by European research groups to bring the company into collaborations. Sometimes, they were just discussions, sometimes they led to proposals and sometimes they led to grants. They were quite frequent; something like that would occur every six to seven weeks. That has now completely stopped.

Q108 **Vicky Ford:** Let's assume that the Government decide they want to be part of the next framework programme. How important is it that you can lead projects, not just participate in them?

Professor Pepper: It is very important.

Professor Morton: If we want to imprint our vision on how these technologies should be developed, clearly we need to be in a position to lead. It is something we noticed with the first round of flagship proposals. There was immediately a great reluctance to allow UK partners to lead, because of the uncertainties in the political situation.

Although there has been involvement, there has been very little UK leadership of such projects and I think that will remain until there is more clarity going forward.

Q109 **Vicky Ford:** There has been very little leadership.

Professor Morton: My perception among the consortia that formed in the current ramp-up phase is that there has been a stepping back in taking leadership roles, because of the current uncertainty.

Q110 **Vicky Ford:** Can we talk about collaboration with other parts of the world? Does that open up new opportunities?

Professor Morton: I would disagree with that phrase. There have always been opportunities to work with Canada, the US, Australia and many other countries. The rationale for such collaborations existed before and will exist after. I would not describe it as a new opportunity.

Jonathan Flint: You are quite right. Those opportunities are there and we should go on exploiting them where they are. The three big players in quantum technologies are the European Union, China and the US. We talked about the ITAR problem in working with the US, although there are still plenty of collaboration opportunities. They will never be fully open with their technology; the US industrial giants will not put fundamental work outside the continental US.

China has its own issues. My businesses are regularly refused export licences, rightly so, for export of quantum technologies to China, so that is not a market we can rely on, and certainly not a collaboration that we can be open with. While there are other opportunities, they are nothing like effective replacements for our long and intimate relationship with the European Union.

Q111 **Chair:** Would you all say that we need certainty quickly and that we should be part of the successor programme?

Jonathan Flint: Yes.

Dr Montanaro: Absolutely.

Q112 **Vicky Ford:** On dual-use restrictions, the US restrictions, are smaller organisations aware of them? I think you said that people are quite aware.

Jonathan Flint: My experience is that you get sent to prison if you are not.

Professor Pepper: Opportunities have always been there. In the past, I have had running in parallel grants from the National Security Agency and the Defence Advanced Research Projects Agency in the US, and from the EU and the EPSRC. There is no impediment to applying for grants from the US. That opportunity has always been there.

Q113 **Liz Kendall:** In the previous session we heard about the need for more and better training for skills in this area, and we have had some written evidence about that. Do you agree? Is there a skills shortage? Where is it, and what do we need to do?

Professor Morton: The lack of skilled people in quantum technologies is currently a key bottleneck not just in the UK but around the world, with the growth of quantum technologies. It is an area that requires some very advanced training, typically at PhD level, but the good news is that the UK made the decision about five years ago to invest heavily in these areas, and the first cohort of PhD students will be graduating in September.

The other message from that is that there is a big time lag from the decision, when you are investing in that advanced level of training, to graduates exiting the training programme and coming into the workplace. That training needs to be maintained for the next phase if we are to continue to provide people for the industry. We also have to look ahead five years to those sorts of needs when thinking about training in future programmes, and perhaps think about other types of qualifications that might be suitable.

The UK can be said to be world leading in training and skills in quantum technologies. In our programme, we have had visitors from Canada and Australia learning about how we run our training programme in quantum technologies, to replicate it. We have been commended by people in industry from around the world who have said that they are not aware of anything like it. That is one thing we are really doing well in the current programme, and we need to continue that.

Q114 **Liz Kendall:** Anyone other than PhDs?

Professor Morton: We should be thinking more about masters-level one-year programmes. The other key point, particularly with PhDs, is that they are increasingly done in partnership with industry. A good goal would be about 50% industrial partnerships. That has the apprenticeship-type advantage that the industries are bringing in expertise through the student who is working with them. Industry is getting exposure to potential students who can go and work there, so it works very well in both directions.

Q115 **Liz Kendall:** Do you mean at PhD level, more at apprenticeship level or some sort of hybrid?

Professor Morton: Given the complexity of the technologies, it will be quite a few years before there is meaningful impact that people can make. The skills required to make a big impact in this area are at the masters or postgraduate level at present.

Jonathan Flint: I slightly differ from my colleague's point of view. As near-to-market products are produced, we will need apprentice-level skills in things like electronics and cryogenics—people who do hands-on manufacture and testing of those very complex things. They do not necessarily need to be PhD level, who will be involved in the design, but they need high levels of practical skills in manufacture.

Q116 **Liz Kendall:** Anybody else?

Dr Montanaro: It is surprising how many students at a slightly earlier level, at undergraduate level, are receiving some training in quantum information or aspects of quantum technologies. For example, Bristol alone graduates 100 students a year who have some knowledge of it through their taught courses. It is a resource that could be built on a lot; as the quantum industry develops, some of those students will go to work for companies directly rather than going into masters or PhD programmes. That is something we can build on and take advantage of.

Professor Pepper: Future quantum products will have a small heart or core that is very sophisticated, but it will be surrounded by products that are more conventional engineering, which can be outsourced. They will require apprentices and skilled engineers in the normal way, as the engineering industry does at the moment, but the small core or heart will be produced in laboratories by physicists at PhD level.

Q117 **Liz Kendall:** Is industry up for that and doing enough about it?

Professor Pepper: Yes, there are a number of engineering companies that one can outsource quite sophisticated products to.

Q118 **Liz Kendall:** How are we doing on gender and ethnic diversity?

Professor Morton: That is something the field of physics and engineering suffers from in general, and the same is true within quantum technologies. It is something we are aware of and make efforts to make progress on.

Q119 **Liz Kendall:** Is that something you should all be thinking about more?

Jonathan Flint: Definitely. As part of the role of the Institute of Physics, we are trying to encourage much greater diversity in the physics community, both in academia and industry. The numbers are getting slightly better, certainly with regard to women in the field. I do not know whether any metrics have been prepared specifically on quantum gender diversity, but in physics it is very poor, although good progress has been made.

Q120 **Chair:** Both on gender and on ethnic diversity.

Jonathan Flint: Yes, it has. For the first time ever, the Institute of Physics in the UK has more female members on its council than male members.

Q121 **Liz Kendall:** Obviously, this is going to be a foundation for the next generation of industry. Are there plans to produce anything a little bit more within society, to think about this? Have you got plans to do something more, considering that it could be a huge area for the future development of this country's science and industry?

Jonathan Flint: The Institute of Physics, across the discipline in general, has programmes for increased diversity, for women in physics, for encouraging girls to take up more physics A-levels and to spread the uptake of technical disciplines away from private schools, which have a strong control on that. It is not really appropriate to have a separate mechanism especially for quantum. In general, with physics and perhaps other technical disciplines, we need much better diversity and to encourage young women particularly to take up careers in STEM disciplines.

Q122 **Darren Jones:** To follow on briefly from that, I was at a dinner last week in Bristol, where I was told that we lose girls around the age of six to seven, because of the drop-off in interest in maths in primary school. To build on Liz's point, we need to try to get them at primary school level.

I have three follow-up questions, one on skills, one on standards and one on regulation. I do not know whether you live in Bristol North West, Dr Montanaro, but I am going to declare you anyway, because I hope that you and your team have huge success in Bristol.

First, on skills, do you feel any tension between holding on to academics in research environments and the inevitable pressure from industry partners to pour your researchers into industry? I have an example. We have a quantum cryptography start-up in Bristol that is really struggling to find post-doc quantum specialists to help it do its business. Clearly, it is a bit of a niche area. How do you think that will work with research, where we are told that we need to continue the fundamental science while moving into this new phase of commercialisation, whereby industry—probably with more money—will want to try to pull you out of the labs and into business?

Dr Montanaro: We are entering a very interesting phase of development. We are already seeing companies offering quite large salaries, in my opinion, to researchers to go and work for them and help them with their efforts. We are already seeing constraints on the number of people we can hire, because of people going into industry. On the other hand, that is a very natural and positive part of the field growing. A way to address it is to attempt to build the capacity we have, so that we have enough people to remain in academia and to do fundamental long-term academic research as well as to go into industry. A key part of that is bringing people into the UK as well as growing our own capacity.

Jonathan Flint: That is absolutely right. If industry is not trying to recruit your academic staff, there is probably something wrong with your academic staff.

Q123 **Darren Jones:** We obviously need to ramp up the numbers of graduates in this phase.

Professor Morton: That's right. It is a key part. It is important to recognise what industry does well and what academia does well. If you are set on building a quantum computer, and at some point, for scaling up, you need to invest in more engineering research, which will not lead to many publications or be suitable for someone on an academic career trajectory, you need to hire skilled people to work on that engineering. That has to happen within an engineering sector; people who want to get involved in that sort of technology development should be naturally drawn into industry.

Professor Pepper: One of the interesting features of recent years is that high-quality PhDs in physics are going into small high-tech companies rather than into the City of London, where they all used to go. Of course, some do, but there has been a general transition, which may be the result of the financial crash in 2008. Certainly, it is very noticeable that they go into small high-tech companies. In this field in general, there is no shortage of people to recruit. There may be a shortage of very good ones, but there is no shortage of people.

Q124 **Darren Jones:** We touched on standards very briefly in the first panel and got the very clear answer that, although standards are helpful, we do not want to get carried away because it might dampen innovation. Do you feel that standards at the moment in your area of work are sufficient, or do you think that getting better quality standards would help you?

Jonathan Flint: It would help if you separate that question between standards in research and standards in production industry. In research, I would probably say that we should keep things free, loose and flexible for as long as possible, because that is what research is; it is doing things that have not been done before, not repeating things that have been done before.

In industry it is a bit different, because people tend to be reluctant to invest in something that has not yet been standardised, because they may be inventing the Betamax of the technology. We are probably not there yet, but where standards are introduced, I would be in favour of them for the more mature products that are close to production rather than for topics that are still in research. Obviously, there are things like safety, which all good labs have, but, beyond that, we should be relatively regulation-free in the research environment.

Professor Morton: It is very sector specific. In something like communication, where two parties are communicating, you need standards so that they can both talk, whether at national or international level. If you are trying to certify security in a communication channel, it needs very careful standardisation and verification. In other sectors, such as computing, there is more market-driven verification. If you are claiming that you can solve someone’s problem faster than anyone else and you do, that is all the verification you need. It varies according to the different types of quantum technologies.

I completely agree that, within a research context, standards are not so appropriate, but in some areas of the underpinning technologies behind research—cryogenics, electronics and the microwave instrumentation that different labs are using—perhaps some standardisation will help to accelerate the research, so that labs need to worry less about the underpinning engineering and pass it on to industry.

Professor Pepper: My colleague Dr Andrew Shields at Toshiba is the chair of the quantum industry group of ETSI. Now it is just called ETSI; originally, it was the European Telecommunications Standards Institute. It has outgrown its European roots, and now has people from Japan, Taiwan and Turkey, outside Europe as we know it, who are busily looking at the question of standards. They have considerable momentum behind them, and engage with their opposite numbers in China and the United States, to ensure that it is uniform, but at the moment the industry is in such a nascent stage that there is not a great deal to do, apart from ensuring compatibility between different pieces of equipment.

Q125 **Darren Jones:** On regulation, in one of the written submissions somebody commented that when thinking about regulation, we should think not just about the regulation of quantum technologies but about what quantum technologies are or will be capable of.

Who is having the debate around the regulation of quantum capabilities and, if no one is having it, who should be?

Professor Morton: This touches on responsible innovation activities. We hosted at UCLQ one of the first workshops on responsible innovation in quantum technologies. There is broad recognition of and excitement about the power of quantum computing. The risks around undermining RSA are well documented. That is one of the most talked-about applications of a quantum computer but the least likely to manifest itself, because, by that stage, I expect that no serious organisation will be using that type of encryption.

One of the concepts that has stuck most around responsible innovation and use in quantum technologies is secure communication. In the current information age, that is very important around data privacy, especially as we move on to the internet of things. We also need to think about questions around security, and whether unhackable and uninterceptable communications are acceptable from a security perspective. That is one of the topics that has come out of the workshops, and I am sure that such dialogues will continue. They should continue.

Q126 **Darren Jones:** Who is having those workshops? Is it UCL?

Professor Morton: We ran one of the first in our responsible innovation unit at UCL, and I believe it has been continued through the national programme by the hubs.

Professor Pepper: It is a problem at the moment. There was a case recently when the FBI wanted to decrypt an Apple phone and Apple would not co-operate. It is a problem with the present technology, and it will become a bit more severe when quantum cryptography enters the domestic arena, but it is something that has to be overcome by other means.

Q127 **Carol Monaghan:** Professor Morton, you have already mentioned some of this, but for the man or woman in the street what are the societal impacts, benefits and risks that you envisage arising out of quantum tech?

Professor Morton: Around quantum sensing, for example, I would point to advances in navigation. What steers autonomous vehicles in the absence of GPS? It could well be a quantum sensor providing that navigation. Around communication, there are topics around security and how we can create security channels that cannot be intercepted, so that you know that your data are secure.

My passion is around quantum computing. We now know how to make a computer that is more powerful than any computer we have currently built today, and we know how to build it. We are going about building a processor that will lead to applications that revolutionise the way technologies advance. It will allow us to design better drugs and build more efficient batteries and better solar cells, as well as superconductors that work for power distribution. It will be a tool that then unlocks a whole range of the other technologies that we will see over the coming decades.

Q128 **Carol Monaghan:** And the risks? Do the rest of you have any ideas?

Jonathan Flint: Like any powerful new technology, it can have unforeseen outputs, as did steam and electricity. Quantum will be no different. In particular, questions around privacy, encryption and surveillance are particularly relevant to the quantum world. I do not think that those worries are any more than with any new change in society.

Q129 **Carol Monaghan:** What about the risk of the technology being developed elsewhere and not here? How would that impact on us?

Professor Pepper: Companies have to sell their goods. Let us say that it is invented in country X, where country X imposes export restrictions on it, which it could well do. But in general companies want to sell their products everywhere.

Jonathan Flint: Quantum products will be cheap to manufacture, once they are finalised. The wealth generation will be in the design, and that requires the intellectual property. We need to maintain in this country the intellectual powerhouse that will generate that IP, so that we can keep control of the technology as it spreads out. We should not just be a manufacturer of cheap widgets for someone else's IP.

Dr Montanaro: Where we would be missing out is in the development of the skilled industry in coming years, which has the potential to be world leading and touches many different aspects of society.

Q130 **Carol Monaghan:** Has sufficient progress been made to replace public key cryptography with quantum-resilient alternatives?

Professor Pepper: That is under way at the moment. Both in the UK and Japan there are testbeds with fairly long links. On the problems that the technology will experience, one just has to increase the length of the fibre over which it can be provided, and progress is taking place there. It is also about whether one can increase the data bit rate; again, progress is being made. There is also progress on enhancing the security of the cryptographic process itself. That is well under way.

Q131 **Darren Jones:** I have an interest in artificial intelligence. We have just done a report on algorithms where we expressed a concern that citizens can get an explanation now, but very few people could understand a machine-learning algorithm to explain it. Is there a risk around some of our quantum and AI companies that there is only a handful of people—maybe you guys—who will have to explain to everybody how it works and what the risks are around it? Will there be a way in which we can understand it more generally without being a professor or a post-doc?

Professor Morton: AI is not necessarily the first application that we foresee for quantum. Ashley will be able to say more on that. I have been to many public engagement talks on quantum computing and quantum AI, and there are ways to communicate the basic functionality of the process that can be expressed to a wider audience. I do not see anything too fundamentally new around quantum computing in that respect.

Jonathan Flint: Maybe that train has already left the station, in that today most people do not understand how most technologies that underpin our society work. I do not understand many technologies. That is not necessarily a problem, but if it goes too far it will be a concern. I do not think that quantum is any different. The way to tackle it is to have an educated workforce with an appreciation for what science and technology can do for us.

Professor Pepper: Quantum is not actually difficult to understand; it is the quantum physicists who make it difficult. That is the problem. With your indulgence, Chair, can I give a very simple explanation of quantum cryptography?

There used to be a demonstration at the Science Museum of the pressure of light, and maybe there still is; I have not been there for a long time. There was a small windmill in a glass case that was about four inches high, and there was a bulb. You pressed the button, the bulb came on, and the arms of the windmill started to rotate because of light pressure. If you were in a dark room and wanted to know where the arms of the windmill were, you would put on the light, but then the arms would rotate, so you would not really know where the arms were. They would be somewhere. That is precisely how quantum cryptography works. The process of measurement actually changes what you measure.

As far as we are concerned, we put the light on and we do not move, because we are bulky objects; but if you are in a subatomic world, the action of taking a measurement changes things. Any attempt to eavesdrop on the stream of photons going along the optical fibre will change their properties, and that can be detected. That is quite simply why it is one of the ultimate methods in security in transmitting information. It is as simple as that.

Darren Jones: Simple.

Q132 **Carol Monaghan:** I am glad you didn't start trying to explain Schrodinger's equation. That might have caused a little bit more confusion. Does quantum tech prompt specific regulatory concerns for AI?

Dr Montanaro: I think it was picked up earlier that the applications may end up being the things that need to be regulated or understood better. It is a very broad technology, and it is akin, if not quite the same, as asking whether we should regulate standard computers. I do not see it as posing any particular concerns connected to AI. The question of whether we will understand the output of a quantum computer is an interesting one, but I feel that the users of the computer will not need to understand quantum mechanics any more than they need to understand how the transistors work in their computers now.

Q133 **Carol Monaghan:** You do not see quantum technologies in their own right raising substantial ethical issues that should be debated publicly.

Dr Montanaro: There is the question about security, which has already been brought up. There is already a fairly good level of public understanding that the RSA cryptosystem is insecure against quantum attack. As for other applications, I do not see anything that really stands out as needing particular public debate along the lines of certain other controversial issues in the past. Of course better public understanding is very important, and some of the outputs of the quantum technologies programme have been focused on public understanding.

Professor Morton: To follow on from that and answer your earlier question, we could be doing more on post quantum. Quantum key distribution is not the only way to get around the weakness of RSA. Better awareness in industry that RSA will be broken over the coming years is important, and I do not think that people are sufficiently aware of that. We should do more to support the adoption of post-quantum methods, and increasing awareness of those methods.

Q134 **Carol Monaghan:** Finally, the national quantum technologies programme includes a responsible research and innovation framework. How well do you think that is working?

Dr Montanaro: As a global entity, it has not affected me directly very much, speaking personally. On the other hand, there are a lot of local initiatives to do with responsible research and innovation, in particular, on public engagement, which are ongoing and very beneficial. For example, academics around the UK who work in my area go to science festivals, give public talks, write articles aimed at the general public, do interviews and all that kind of thing. That has been very helpful indeed.

Chair: Thank you all very much indeed. It has been a fascinating session. We appreciate your time. I am sorry that we have overrun. You kept us talking. Thank you.