Responsible Technology Institute

UNIVERSITY OF OXFORD

Creating a Responsible Quantum Future

The case for a dedicated national resource for responsible quantum computing

UKRI Engineering and Physical Sciences Research Council

Contents

Executive summary

Background

Quantum computing may be closer now than previously predicted – the pace of research is accelerating and timescales around when useful outputs and workable quantum computing systems might be available seem to have shortened.

As with many novel technologies, quantum computing is highly likely to engender societal changes, and previous experience with large-scale technologies and innovations such as Nuclear, Genetically Modified Organisms (GMOs) and Machine Learning, demonstrates that such changes are not always beneficial, or that benefits are not shared equitably in society. Negative consequences of such innovations can undermine trust, negate potential benefits, and may cause actual harms. Research shows[1] that societal attitudes towards quantum computing and quantum technologies are currently reasonably positive – and in order to maintain (and be worthy of) societal trust and acceptance, good governance is essential. The UK National Quantum Technologies Programme (NQTP) Statement of Strategic Intent[2] rightly says that "*quantum computing could impact on society [in ways that] are so profound it is hard to ignore*", and the National Quantum Computing Centre (NQCC)[3] repeatedly highlights the need for the UK to deliver societal benefits, prosperity, and security.

> *Quantum computing is highly likely to engender societal changes*

Governance can be responsive (typically legislation or regulation after harm has been caused or a need is perceived) or pre-emptive (utilising anticipatory techniques, and aspects of responsibility such as care and responsiveness).

1. EPSRC. (2017). *Quantum Technologies Public Dialogue Report*.
2. https://uknqt.ukri.org/files/strategicintent2020/
3. https://www.nqcc.ac.uk/wp-content/uploads/2020/09/NQCC-Strategic-Intent-v1.0.pdf

Pre-emptive governance work in the form of Responsible Innovation (RI – also known as Responsible Research and Innovation, or RRI) was included in the Networked Quantum Information Technologies (NQIT) Hub at its inception; but was not carried forward systematically in the Quantum Computing and Simulation Hub that succeeded it. A follow up project to the NQIT-RRI[4] work was designed by the same team of RI investigators that had worked on NQIT to ascertain whether there was a perceived need for ongoing RI work in the field.

"Questions of Responsibility" – Impact Acceleration Award Research Project

Our project "Towards a Hub in Responsible Innovation for Quantum Computing" was funded by an Impact Acceleration Award from the University of Oxford. The research, consisting mainly of one-to-one interviews with key informants, took place between April 2020 and May 2021. The work plan was considerably altered because of the COVID-19 emergency.

The conclusion from the findings of our investigations in this project is that such a need is indeed perceived – indeed actively desired – by many of those working on the development of quantum computing. After qualitative research work in policy, academia, and industry loci for quantum computing over the last several months, we have a snapshot of the quantum computing landscape. This has led us to make several recommendations.

Recommendations

We perceive the need for:

1. **A Responsible Innovation hub for quantum computing.** The infrastructure of the quantum computing programme in the UK has altered with the creation of the National Quantum Computing Centre, but the need for a responsible innovation outlook has only increased with the relatively closer prospect of commercialisable quantum computing. The NQCC would be a key player with involvement in pre-emptive governance activities.

2. **Central government investment.** Government participation, through the National Quantum Technologies Programme and in other ways, can create capacity, demonstrate confidence, maintain a public-sector interest in the

4. For that project we used the alternative term Responsible Research and Innovation (RRI)

technology, and provide ongoing governance with the appropriate level of granularity.

3. **Horizon planning.** Development of the sector is moving at pace and it is vital to guide its development in order to try and ensure beneficial societal impacts and public trust.

4. **Stakeholder input.** There are numerous bodies and institutions that will be affected by quantum computing technologies and there is an urgent need to bring them up to speed and involve them in discussions around development.

5. **An International viewpoint.** Quantum computing is a nation-state level technology with a high degree of competitiveness internationally. The need to balance benefits to society as a whole while mitigating risks of potential misuse and protecting the UK's investment is a core theme of responsible and trusted research and innovation. The UK should take an active part in the CEN-CENELEC Focus Group and ETSI standards groups on quantum technologies.

Quantum computing is a nation-state level technology with a high degree of competitiveness internationally

We conclude that the UK requires a roadmap for the responsible development of quantum computing technologies, and we here suggest such a roadmap for discussion and development.

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Background

Quantum computers

The last two decades have seen rapid and accelerating developments in the quantum computing field. A quantum computer uses 'quantum bits' (qubits) to perform its operations, harnessing quantum mechanical phenomena of superposition and entanglement to outperform a classical computer in particular types of calculation such as, large-number factoring and optimisation of multiple variables (Lu, 2019). Quantum physics also enables features which are not possible classically: these include true randomisation (Aaronson, 2014) and simulation of processes at the quantum level (Feynman, 1982). The advantages that may attach to such performance are generating enormous amounts of interest from the world's largest technology companies as well as many research-focused organisations, and significant sums are being invested into building quantum computers (Gibney, 2019). Gibney (2019) also points out that the sector is increasingly populated by start-ups in Quantum Computing Technologies (QCT)-adjacent technological development, (for example specialised start-ups in fields such as "deep physics", in ways to implement qubits, in quantum algorithms, and in quantum communications), which demonstrates a move beyond the research phases of this work and into commercialisation. Globally, the quantum computing market was estimated to be worth £389m in 2019, with predicted growth to £50bn by 2030 (ResearchAndMarkets.com, 2020).

A quantum computer uses 'quantum bits' (qubits) to perform its operations, harnessing quantum mechanical phenomena of superposition and entanglement to outperform a classical computer in particular types of calculation

Novel technologies such as QCTs can affect society in both positive and negative ways, as has been seen with various other technologies such as Machine Learning. Machine Learning can provide significant advantages in fields

that handle large quantities of data and have a focus on pattern-recognition. This facility has enabled major advances in, for example, skin-cancer care – the trained Machine Learning model has proven to be adept at helping to identify cancerous lesions (Hekler et al., 2019). However, this same Machine Learning technology, when used for facial recognition applications, has been shown both to entrench and amplify existing biases in both data and practice against people of colour (Garvie, 2019). Negative impacts such as these on society can and do cause societal pushback and loss of trust – in the case of facial recognition, for example, there are growing campaigns to outlaw its use. IBM, among others, has recently announced a halt to its facial recognition work (Krishna, 2020), and several cities around the world have prevented local law enforcement agencies from using the technology. This gives rise to the possibility that the positive uses of Machine Learning may become 'tainted' by those that are perceived to have negative effects. The example of Machine Learning shows that the ways in which new technologies are driven, shaped, introduced, and regulated can be critical both for societal acceptance and to ensure that society can receive the benefits while limiting possible negative effects.

Societal effects

The affordances of quantum computing may also have significant effects on society. Predictions of these affordances are varied – for example QCTs may allow for high-speed optimisation of large numbers of variables, or simulation of quantum processes, making them valuable for new drug discovery and many other fields. On the negative side of these possible affordances, it is widely agreed that quantum computing of sufficient capacity is likely to have the ability to break existing cybersecurity protocols through rapid large-number factoring (Vermeer & Peet, 2020). Clearly, the importance of secure communications in an era of embedded and growing Internet dependence is vital, so in order for the positive aspects of quantum computing to be realised, potential negative effects such as the impact on cybersecurity must be minimised to try and ensure that society can and will trust the technology. The threat to secure communications is already being addressed by post-quantum cryptography (Bernstein, 2009), but as with Machine Learning and internet technologies, it is not possible to predict with any certainty what the societal impacts will be some years into the future.

In order for the positive aspects of quantum computing to be realised, potential negative effects must be minimised

Efforts have already been made to engage with publics on quantum computing technologies – the Public Dialogue exercise carried out in 2017 represented a significant outreach operation that aimed to assess public understandings of quantum and levels of confidence in the technology (EPSRC, 2017). It found that "*support for the development of quantum technologies grew as people's understanding increased, provided that research was subject to proportionate governance mechanisms.*" The House of Commons Science & Technology Committee too has addressed this, supporting the call for governance and the need for public confidence in the technology (House of Commons Science and Technology Committee, 2019).

Governance approaches

Governance can broadly be divided into two types – retrospective (backward-looking) and anticipatory (or forward-looking). Retrospective types – 'hard' governance – include regulation and legislation and are not usually instigated until harms have already occurred. Prospective, forward-looking or 'soft' forms of governance include Responsible Innovation and other approaches (such as Real-Time Technology Assessment and Participatory Design) that seek to improve societal outcomes and prevent harms from occurring.

'Hard' governance

It is possible and even likely that quantum computing technologies will, in the future, require regulation. However, regulatory processes are less than ideal for technological challenges that may be subtle, complex and fast moving. Regulation is generally slow, is often difficult to accomplish, and is generally reactive rather than pre-emptive – usually meaning that harm has already occurred. In addition, waiting for a regulatory infrastructure can also leave spaces for disruptive technologies to burgeon at high speed. This is readily demonstrated by examples such as Airbnb, which took advantage of lacunae in existing law and has now created such significant societal problems that cities across the world are actively trying to limit its reach (Chee, 2020). There is currently no UK legislation that specifically applies to quantum technologies – these technologies are at such an early stage that it would not be a good use of legislative time to enact laws or regulations that may never be needed or may be inapplicable. In the case of quantum, therefore, 'soft' approaches to governance may seem to be indicated.

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'Soft' governance

If possible, it is better to address challenges before they arise than to wait for harms to occur, particularly when such harms are likely to undermine societal trust in the technology (as in the Machine Learning examples above). 'Hard' governance tools such as regulation can be supplemented, rounded-out and supported by 'soft' governance approaches that have the advantage not only of trying to pre-empt problems, but of providing the agility and granularity necessary to respond to rapidly developing situations. These approaches are anticipatory, reflective, inclusive, creative, and responsive (Stilgoe, Owen, & Macnaghten, 2013), rather than backward-looking and restrictive.

There is some work being carried out on prospective governance within quantum – for example, the IEEE is looking at preliminary informal standards around performance benchmarks and terminology in quantum computing (IEEE, 2019) and there are also quantum industry bodies such as the Quantum Economic Development Consortium (QED-C) in the US that seek to proactively create codes of conduct. These approaches focus on the creation of high-level agreements that can form a well-regulated market in the quantum computing industrial sector. There are also some high-profile calls for a 'quantum ethics' that can reflect and advise on some of these societal challenges (Khan, 2021), and a series of workshops on societal risks by the World Economic Forum working towards a set of principles for quantum computing governance.

There are also some high-profile calls for a 'quantum ethics'

However, these approaches, although essential as part of a comprehensive governance framework, may be regarded as insufficient. They are focused either on technical standards (such as the meaning of quantum 'advantage') and the action of the marketplace, or high-level questions around concepts such as justice and beneficence. These are certainly necessary, but omit several key factors that, we argue, also need to be considered. For example, standards-based approaches do not take into account the societal impacts of these novel technologies, nor do they address questions of innovators' responsibilities.

It was concerns such as these – of societal impact and the responsibility of innovators – that led to the incorporation of a Responsible Innovation strand in the first phase of the UK's quantum computing Hub, Networked Quantum

Information Technologies (NQIT). The quantum computing Hub was one of four quantum Hubs – the others focused on quantum sensing; imaging; and communications (EPSRC, 2020). The UK is not the only jurisdiction to consider prospective governance to be key – there are calls in the US for a 'soft law' approach that retains agility while also protecting end-users (Johnson, 2019). However, the Responsible Innovation work was not renewed in 2019 with the same level of resources when the Quantum Computing and Simulation Hub took forward the work of NQIT, despite recommendations to do so (House of Commons Science and Technology Committee, 2019).

Responsible Innovation

There are many methods for trying to respond in an iterative, agile manner to the challenges presented by emerging technologies. Responsible Innovation (RI) is only one such approach. Although definitions of RI vary, perhaps the most useful comes from the RRI Tools project:

> *"RRI is a way to do research that takes a long-term perspective on the type of world in which we want to live… [RRI means] involving society in science and innovation 'very upstream' in the processes of R&I to align its outcomes with the values of society."* (www.rri-tools.eu)

Responsible Innovation is a way to do research that takes a long-term perspective on the type of world in which we want to live

This definition emphasises the long-term view, and societal impact, as well as the necessity for reflecting on the features we want our future to have. The other significant features are the need to instigate such soft governance at early stages in developmental processes, and to involve the society within which the technology will operate. These requirements are semi-formalised within the Anticipate-Reflect-Engage-Act (AREA) Framework that has been adopted by the EPSRC in the UK (Stilgoe et al., 2013).

The RI methodology, drawing on this Framework, combines consultation with those who may be affected; consideration of both negative and positive outcomes; and potentially influencing the course of a technology if deemed necessary. RI has gained attention since the turn of the century, partially as a response to some of the public failures around emerging science of the last few decades, such as the BSE crisis and genetically modified organisms (GMOs), and has become embedded within European and UK policy frameworks

(de Saille, 2015). RI aims to ensure that research and innovation are carried out *for* and *with* society in order both to increase acceptance and to improve outcomes for society (Owen, Macnaghten, & Stilgoe, 2012). There is work on Responsible Innovation in nanotechnology (Pandza & Ellwood, 2013), in synthetic biology (Ribeiro & Shapira, 2019) and in climate engineering (Stilgoe et al., 2013) – all complex, large-scale novel technologies. This makes Responsible Innovation a useful candidate for trying to anticipate and respond to the potential societal impacts of QCTs.

> *RI aims to ensure that research and innovation are carried out* for *and* with *society*

Responsible Innovation in NQIT

RI was a core work package in the Networked Quantum Information Technologies (NQIT) Hub, one of the four research hubs funded as part of the UK National Quantum Technologies Programme. The work aimed to:

- provide a background to RI within the computing hub;
- identify the challenges for RI in NQIT;
- make recommendations about how to handle these challenges;
- and finally describe a framework and pathway to implement a tailored RI process in NQIT
  (Inglesant, Hartswood, & Jirotka, 2016).

NQIT-RRI focused on qualitative techniques for its study. Quantum technologies as a field is highly specialised, very focused, and relatively small, meaning that in general qualitative work was deemed to be more useful for the questions the research sought to investigate. What the project examined in depth was not just the state of the art in terms of technical progress, and how this might relate to societal impacts, but also the positions of the researchers and engineers themselves in relation to societal concerns and the technologies they were progressing in their work.

The methods included interviews, case studies, focus groups, a workshop focused on defence and national security issues in quantum, and ultimately a series of roadshow workshops to demonstrate and disseminate the work of all four Hubs. The research was not only investigating and tracking the Responsible Innovation approaches within the Hub but simultaneously co-creating them in a

participatory, action research modality. It is important to note that the focus of the NQIT-RRI team was not to be responsible for all the RI activity in the Hub, but rather to act as sources of expertise, generators of discussion, and facilitators of RI-focused conversations. The team produced reports and policy briefings that aimed to engage with stakeholders and create a resource that could be accessed by those assessing future work, including a survey of the landscape of RRI in quantum computing (Inglesant et al., 2016) and a report of the defence implications (Inglesant, Jirotka, & Hartswood, 2018).

The work of the NQIT Hub concluded in November 2019. Subsequently, a further round of funding supported the creation of the UK Quantum Computing and Simulation Hub (QCS) as part of the second phase of the UK's quantum effort, with funding ongoing until 2024. Funding via UK Research and Innovation (UKRI) has also created a National Quantum Computing Centre, which will act as a central hub for the UK's quantum computing community (UK NQTP, 2019).

However, the RI work that had been included in the NQIT project was not funded in QCS in terms of providing expert support and personnel. The NQIT-RRI project team therefore sought independent funding to assess whether there was a need for the creation of a Responsible Innovation Hub. Such a Hub would be in a position to provide specialist support and expertise to the quantum technologies community.

Responsible Innovation Hub research project

Given the acceleration of progress within quantum computing research and technological development, and the absence of a dedicated responsible innovation resource within the second round of the quantum computing hub, this is now the time for assessing the need for an ongoing, specialist RI approach within quantum computing technologies. It is clear from rapid advances such as Google's claim to have achieved quantum advantage (Murgia & Waters, 2019), the emergence of specialist quantum computing development companies, the availability of cloud-based access to early quantum computers such as IBM Quantum[5] and development environments, that the sector and the technology are moving fast. These factors led the NQIT-RRI team to seek an Oxford University Impact Acceleration Award in order to carry out a 'snapshot' of ongoing work on quantum computing.

The research was carried out from October 2020 to January 2021. 40 individuals working in the quantum computing sector were approached for interview. These individuals work across academia, in industry start-ups, and in policymaking areas. Of these 40, 20 agreed to participate.
Table 1 shows the distribution of roles among the participants: n>20 because some participants held more than one position (eg a university position and also a business role). Participants were asked to elaborate on their views from both perspectives.

Table 1

Industry	7
Policy	5
Academia	10

Interviews were semi-structured, following the same broad framework of questions each time, but with scope to discuss questions in more depth if participants were happy to expand on points, and to allow space for

5. https://quantum-computing.ibm.com/

investigating potentially useful avenues. The average length of a discussion was 35-40 minutes. Interviews were given a randomly allocated numerical code. Transcriptions were redacted at the point of transfer from voice to text, then loaded into NVivo qualitative analysis software[6]. Analysis was carried out inductively, with themes emerging from the written transcripts of the interviews through an open coding process (Braun & Clarke, 2006).

Limitations

1. The research study was relatively small and relatively brief. Further work may be needed across a broader spectrum of quantum sector participants to gain a wider perspective on these findings – this could be done through the use of a survey instrument.

2. It is possible that those who agreed to participate in the study were already biased in favour of responsible innovation approaches – a broader survey as suggested above could attract a wider variety of views.

6. https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home

Research findings

Several themes emerged from the interviews:

- **i.** A need for Responsible Innovation
- **ii.** Consideration of societal impacts
- **iii.** Increase in 'national' approaches
- **iv.** The impact of investment

The key points are summarised below, before we examine the implications and offer recommendations for further research and practice.

A need for responsible innovation

In academia

Participants working in quantum fields of research were quick to argue for the necessity of responsible innovation approaches. Insights ranged from the perceived necessity of engaging with stakeholders and publics, to a requirement for anticipatory work that could examine possible benefits and downsides.

Participants working in quantum fields of research were quick to argue for the necessity of responsible innovation approaches

> *"what we are all doing on a day to day basis may have a very significant impact on society. And therefore, we must be conscious of that, we must answer questions of society about any concerns or worries or hopes that they may have for this technology. So … we have an obligation to engage."* I7

> *"for people that are on the brink of building a world changing technology, you should think seriously about what you're doing"* I11

> *"what I wanted… was to create a whole series of [reports] - and to directly impact the public, to directly impact sectors, to directly impact policy. And to have a much higher profile."* I15

However, it was also clear that there was limited capacity for undertaking work such as this. Although academics were certain their work was being carried out in accordance with well-understood research integrity frameworks, familiar from training and from peer-review processes, they also understood that the requirements of Responsible Innovation go several steps beyond such frameworks and operationalise a long-term perspective that links current work to future consequences. Taking these steps was viewed as something beyond their training, experience, and possibly beyond their remit, which is still seen as the production of 'good science'.

> *"I haven't spent a lot of time thinking about whether it would be desirable to have better machine learning classifiers and whether it would be desirable to live in a world where there's an algorithm that's analysing your transaction data…"* I11

In industry

As research moves beyond foundational science into 'innovation' or developmental phases and adoption by industry, commercialisation imperatives (making products that can be sold) render possible concerns about impact more immediate. Again, the requirement for Responsible Innovation was clear to participants, and the potential impact on industry should there be substantial public pushback or science scandals.

> *"The big example for me … is how it all went with nuclear. And, you know, nuclear was another … high prospects, physics-led innovation … and whatever you might think about the merits … there's a whole difficulty, because of the way the perception of the industry has developed."* I13

> *"I see responsible innovation as very important - as a thing for everyone to think about."* I10

"if you think about, if you deal in a responsible way it's ingrained in your… company culture." I17

But this need to embed RI into company culture is – particularly in smaller start-ups and SMEs[7] – potentially in tension with the requirements of large venture-capital investors, who may be unwilling to support approaches that they may view as constraining creativity, or that may affect (for example) decisions around where to purchase resources, or have work carried out. Smaller companies may find it extremely challenging to devote resource to RI training, concerns or initiatives, particularly when they are required to make a return on investment. The lack of either incentives or compliance requirements for RI measures makes it a low priority.

Smaller companies may find it extremely challenging to devote resource to RI training, concerns or initiatives

In policymaking

Interviews with policymakers demonstrated their understanding of 'de facto' responsible innovation-type approaches within their own work. This might be through such measures as i) using anticipatory approaches to consider possible benefits or harms; ii) engaging with stakeholders; and iii) understanding the ability to affect trajectories by becoming involved at 'upstream' points. This applied even if they were not specifically using terms that included 'responsibility'. Those involved in overseeing the creation of a quantum sector were particularly aware of the potential impact of negative outcomes on a burgeoning industry. RI is seen as a tool with which to manage the risks associated with new technologies in terms of providing a guardrail approach.

"I described it as crucial because it is…. you can cripple an industry before it even gets going. Because you don't even, you don't even impact the dialogue in any meaningful way. You can say it's safe, and people won't believe you." I15

"responsible innovation - you know, it is an important part of the programme as a whole, not just for [quantum] computing. And at the

7. Small-to-medium sized enterprises are defined in the UK as companies with two out of three of: fewer than 250 employees; turnover less than £25m; gross assets of less than £12.5m

moment, I don't think it's planned in to the programme in terms of the forward look, but it's something we would like to be!" I19

"this is the stuff we need to be thinking more about" I20

This recognition of the need for anticipation, engagement and early influence on trajectories is valuable

This recognition of the need for anticipation, engagement and early influence on trajectories is valuable, but can only be of limited value if all of the outreach comes from one side of the discussion.

Consideration of societal impacts

In some respects, the potential impacts on society are already being considered, particularly those that affect security. The dual-use nature of quantum computing has ensured that it is part of the purview of organisations such as the MoD, NCSC and GCHQ to consider its possibilities. However, interviewees were clear that these considerations are not necessarily being applied in wider societal contexts.

"there is always, there needs to be this thought of society in terms of impact" I17

"we're talking about timelines on quantum computers and capabilities, but you know, what else? What are we … missing here? When it comes to societal impact, whether it's economic or quality of life" I07

Interviewees were almost uniformly aware of a sense of urgency in terms of considering the possible impacts of quantum computing technologies on society, and also displayed a strong awareness that no organisation or group is currently tasked with either undertaking or drawing together work on societal impact.

Increase in 'national' approaches

The nature of quantum computing research is such that it requires significant levels of support in terms of resource. Building a quantum computer is now also being seen as a matter of national prestige, in addition to potential impacts on cybersecurity, discussed above, if a quantum computer were available to a rival nation or non-state actors.

"there was a tweet by…Ivanka Trump[8] … going 'yep, US declares quantum supremacy'" I10

All these factors contribute to governments now taking considerably greater interest in the progress of quantum computing, and participants in the study agreed that the research had become an international 'race'. They cited phrases such as 'sovereign capability' that were now being heard more frequently in policy-related discourse.

> *Phrases such as 'sovereign capability' [are] now being heard more frequently in policy-related discourse*

"it's becoming a bit geopolitical… China's Premier … mentioned the need for China to invest in quantum technology … Europe has a programme, the UK has its own programme, and the US recently announced a programme last year." I11

"we've seen this …in quantum key distribution… there's a … big US-China rivalry that's …developed. And we're also seeing it quantum computing" I10

Many interviewees were pragmatic about whether the UK would be able to compete in such a race in the longer term, given that much larger players with much deeper pockets were now on the field.

"America wants one, and China wants one, and … you can only have a certain number" I14

Optimism remained, however, about the UK's standing in this international race, given its genuinely world-leading progress in many quantum computing technologies, but the most realistic model to aim for was seen as similar to that in Singapore, Taiwan, Japan and other countries with highly focused and relatively powerful technology sectors. The UK has the ability to position itself as a key component in the global supply chain, which in the longer term may be more valuable than being the first to build a scalable quantum computer.

8. https://twitter.com/IvankaTrump/status/1186987509609385988

The impact of public investment

> *There was concern in some quarters that large amounts of funding in academia were encouraging people to make their projects sound more "quantum-y"*

Interviewees were divided about the levels of investment in quantum and its effects. There was concern in some quarters that large amounts of funding in academia were encouraging people to make their projects sound more "quantum-y" in order to be able to respond to funding calls, and some noted that large awards had generated professional jealousies and tensions in a field that until fairly recently had been a relatively small and closely collaborative community. These outcomes may be viewed as undesirable but need to be balanced by alternate concerns that insufficient investment over a number of years has led to capacity challenges that can already be seen in academia.

> *"lots of places want to fund this research but they're not finding the people to hire … because … governments were not funding the PhD students and postdocs to work in this area."* I10

> *"we're already seeing this at senior level, where… many of the people … have been snapped up by large companies and also by by start-ups … We have several projects … that we're really struggling to hire people for"* I10

Towards the innovation and commercialisation end of the sector, the concern was again that there was insufficient funding available to truly enable a flourishing quantum sector, and that the capacity shortages being seen in academia may well be carried forward to commercial sectors in the future as start-ups struggle to expand. This is also tied up with concerns that lack of investment will make it challenging to retain talent in the UK – foreign or private investment may encourage teams to move to other regions – creating further capacity issues.

> *"he's raised $400 million … and he's taken the workforce out of the UK."* I15

Capacity is also not the only issue caused by a lack of investment. A further domino-effect concern was that this type of research – once it starts to be increasingly carried out within private companies – becomes subject to many

more limitations imposed by the need to protect intellectual property and operate in a highly competitive environment.

> *"there are probably increasingly numbers of programmes … in various regions, where it's not … visible what researchers are doing anymore."* I07

Also expressed was the likelihood that – should private companies become the primary investors in this potentially extremely high-value sector – the impact on societies was likely to be less beneficial than if control over quantum computing capacity is widely and equitably shared, supported by public investment.

> *"if the result is that these companies end up being the ones that have the only quantum computer in the world … then this is not necessarily a good thing for humanity"* I10

Another reason for government to be a major investor in this sector is that quantum start-ups may have a long gestation period before returns can be made. Additionally, like any nascent sector, there is likely to be a high percentage of failures. Investment is needed for these relatively high-risk, slow-burn start-ups from investors with deep pockets who are willing to potentially wait a considerable time for a return on investment.

Investment is needed for these relatively high-risk, slow-burn start-ups from investors with deep pockets

> *"an industry has to grow and then be self-sustaining and expanding, but you've got to support it until then and you've got to give it confidence - so government, in my view, needs to be the first customer."* I15

> *"enabling companies to get access to finance … is a key issue … because there are concerns that the UK market just doesn't have the right sorts of funds to continue to invest."* I19

Discussion and implications

Responsible Innovation has been applied in a number of emerging and fundamental areas of technology, including ICTs (in a project led by one of the authors of this roadmap[9]) and in earlier stages of quantum computing in the NQIT Hub (led again by this author and another author was the main researcher). It might be argued that quantum computing is not sufficiently different from other technologies to require a separate RI effort. We argue, however, that quantum computing has distinguishing features which are quite different from classical computing and requires a distinct approach. Participants in this research were clear that quantum computing is a powerful technology, of great potential significance to the UK economy, though in ways that are not yet clear, in use-cases that are as yet unknown, and in a timeframe that is also subject to significant shifts. Additionally, these rapidly developing innovations are set within a continually shifting and highly competitive international context. In the face of uncertainties like these, there would seem to be a clear and present need for well-defined channels of communication among policy, research, and industry, an ability to respond rapidly to new developments, a cohesive policy and governance strategy, and a programme of outreach to stakeholders including civil society.

Quantum computing has distinguishing features which are quite different from classical computing and requires a distinct approach

Responsible Innovation resourcing

Many of the requirements detailed above are within the remit of high-level public policy, and would be beyond the scope of this report to discuss in any depth, but our interviewees clearly expressed the importance of responsible innovation, broadly understood. Although participants demonstrated a range

9. Framework for RRI in ICT - https://www.cs.ox.ac.uk/projects/frriict/index.html

of understanding of responsible innovation principles, there was unanimity on the importance of 'responsible' approaches and the need to be very clear with those potentially affected – stakeholders including the general public – about what may be coming over the horizon. What was equally clear was the dearth of resource dedicated to carrying through such responsible innovation approaches. **Without such resources, these issues, while recognised as important, risk being swept away in the tide of innovation.**

Participants expressed disappointment in the lack of resource when it came to responsible innovation expertise for them to call on. One interviewee commented that they would keep a dedicated responsible innovation person "really busy" – responsible innovation approaches are viewed by the majority as bringing a valuable perspective that is seen as essential in helping support the quantum sector as it finds its way to maturity.

Participants expressed disappointment in the lack of resource when it came to responsible innovation expertise

Consistent, focused Responsible Innovation

In particular, this research identified a need to consider societal impacts. In some very specialised respects this is being addressed, but where such consideration is taking place, it is either very focused on one particular aspect – such as post-quantum cryptography – or it is very piecemeal, as demonstrated by the regulatory and policymaking participants who expressed frustration at the disjointed approaches they perceive in these areas. It was clear that some of the policymakers interviewed had carried out horizon-scanning, anticipatory work and perceived a need to engage with the quantum sector – however, an RI approach within the quantum computing field would have demonstrated a need to engage on *their* part. Such reaching-out to potentially-affected sectors on a systematic basis should be a part of a well-rounded and thorough RI approach, embedded throughout quantum computing fields – participants did not see this happening in a programmatic way.

Potential impacts of investment shortage

Participants discussed the numerous problems that could arise from a lack of financial support, some of which only come to light as knock-on effects from others.

One of the obvious impacts is that restricted funding creates capacity shortages at PhD level. This then has implications not only for ongoing academic research projects but also creates skills shortages in industry, and may lead to relocation of key companies to other countries and/or the departure of skilled professionals ('brain drains'). Lack of the right type of investment may also mean that grassroots areas of the sector are hindered in their ability to grow (for example the challenge of companies that spin out from universities no longer having access to university hardware, which can be enormously expensive to replace), leaving the UK trailing internationally and unable to compete for supply-chain roles.

Other impacts are also likely from under-investment. In a sector where highly competitive and well-funded private sector companies are either buying up start-ups, investing in them, or taking in large numbers of postgraduates, a privatisation of quantum computing would likely prevent government from remaining closely engaged with developments across the sector. Additionally, when private companies invest in research, that research may tend to be guarded as intellectual property within those companies, rather than made public. A large-scale private company takeover of the sector could create a situation where public bodies are entirely dependent on the private sector for their quantum computing supply requirements.

However, perhaps the most significant effect of under-investment would be the impact on governance, and the potential implications for public trust.

Perhaps the most significant effect of under-investment would be the impact on governance

Governance

As previously discussed, 'soft' governance approaches are more flexible than 'hard' approaches and do not need to wait until harms have been caused. Responsible innovation is only one such pre-emptive approach, but what all such approaches have in common is that they aim to prevent harm by operating proactively rather than reactively. A lack of government investment, discussed above, could result in state government effectively being 'shut out' from the sector. This would render effective soft governance extremely difficult. Given the need, and public demand, for governance of novel technologies such as quantum, it would seem clear that policymakers and governmental agencies need to remain well-informed and

closely involved with the quantum sector. Government that retains involvement in the sector through a variety of levers (many of them necessarily economic) at different levels of granularity – such as funding for projects, capital support for equipment, investment in startups, committee oversight, and other mechanisms – is more likely to retain the influence needed for 'soft' governance. A lack of such governance levers may create a perception that this novel technology is essentially 'ungoverned'.

Recommendations

It is clear from this research, carried out in all three strands of the triple-helix model (academia, industry and policy), that quantum computing – although still a nascent technology – has the potential to form a highly significant and influential sector of the UK economy, in terms of both finance and impact. Not only is access to stable quantum computing capacity likely to have important effects on other sectors (such as pharmaceuticals, finance, manufacturing, distribution), but UK specialist quantum component companies have the opportunity to form a valuable and specialised part of the worldwide quantum computing industry. The effects of the growing optimism around quantum computing are already being felt, as reports into the growth of the sector show, and it is evident to those closely involved that the pace of development and change has increased. This research has demonstrated some of the challenges faced by those in the field and the issues that they view as important.

The potential importance and impact of quantum computing therefore make it crucial to retain and support a relationship of trust with society throughout the process of sectoral growth and establishment, as well as to retain the ability to guide and influence that sectoral growth. Societal concerns have already been discussed in the House of Commons Science and Technology Committee report (House of Commons Science and Technology Committee, 2019), which reflected on the public's requirement for governance in quantum computing technologies. There are many possible modes for governance in the area but given the rapidity of change and the need for iterative, agile and responsive guardrails, it is our recommendation that Responsible Innovation approaches should be explored in a more focused way. This gives rise to specific recommendations in several areas.

It is our recommendation that Responsible Innovation approaches should be explored in a more focused way

Responsible Innovation Hub for quantum computing technologies

For all the reasons given above, this report highlights the need for a central responsible-innovation-focused resource. This Hub would be designed to expand on the advisory role of the NQIT-RRI project that focused on Responsible Innovation training and consultation and would operate as a central contact for RI work in quantum computing, drawing together the various groups and interests in quantum, for work encompassing:

- offering direct RI advice to projects and start-ups
- organising liaison work with stakeholders
- serving as a point of contact for policy
- improving understanding of responsible innovation among students, researchers and early adopters
- anticipating and addressing some of the broader challenges that may hinder adoption of responsible innovation mindsets

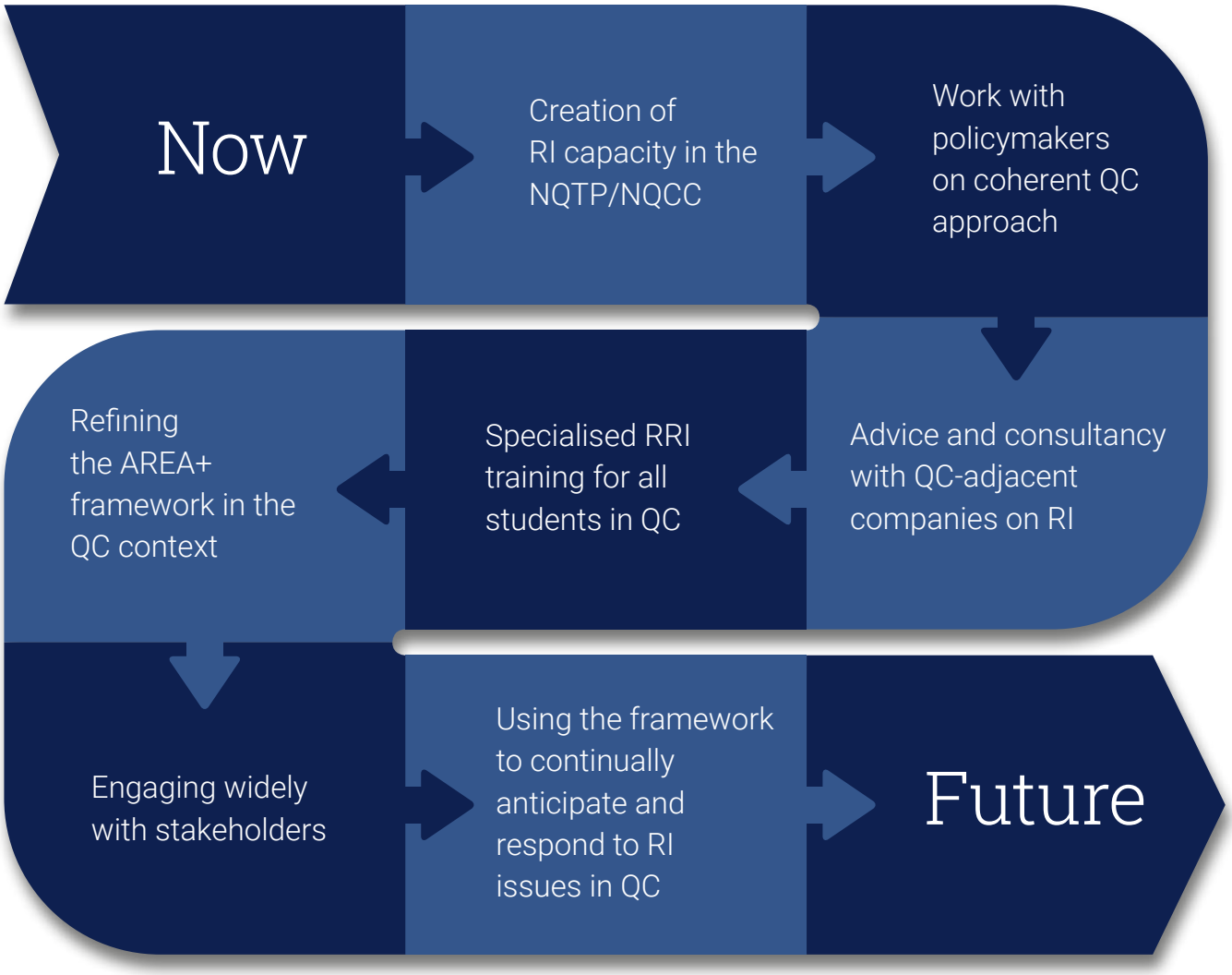
The research on which this report is based has demonstrated the need for a much more in-depth approach to responsible innovation in quantum computing, one that understands the commercialisation imperatives of the sector; the investment needs; the governance options; the unique way in which much quantum computing research is being carried out; the international context; and the options available to the UK in terms of its global positioning, as well as the fundamentals of responsible innovation.

Such an approach must encompass actors across the triple helix, and, at the confluence of academia and industry providing a core resource as part of the UK National Quantum Strategy, we suggest that the new National Quantum Computing Centre is a key player in this work. The details of this involvement would be discussed with Directors of the NQCC if, as we hope, an RI Hub is supported and resourced, but could include acting as a permanent organisational locus for this work (actual physical presence is likely to be minimal, with most work done remotely or at visits to companies and research centres) and mediating between the RI Hub and early adopters and other stakeholders. The Hub's role would also encompass monitoring and recording global developments in the implementation and societal impact of quantum

information technologies and be a resource as a centre of expertise for policy makers and other stakeholders. Alternative locations would also be feasible as long as the Hub was 'hosted' by an organisation eligible for funding. The User Engagement team of the QCS Hub also have an important role.

A roadmap for an RI Hub in quantum

Although further research would be required to create any detailed roadmapping recommendations, certain milestones would stand out. These could include:



Suggested roadmap for the development of RI in quantum computing

Key points on the roadmap would iterate or shift focus depending on the development of the field and the sector, but the general trend would be to embed RI throughout the research, development and commercialisation process, while also working with policymakers at national and international level to develop coherent strategies for the ongoing development of QC. The roadmap does

not have an end-point as such because the nature of carrying out responsible innovation work means that it is never 'done' – rather it is an ongoing process that develops as the technology develops. Mature technologies will have different impacts and different requirements than during the growth period, but oversight and responsiveness will still be required.

Investment

Significant investment in the sector must come from government. Government must be an early customer and also a supporter of the sector, working to leverage private investment in the UK's world-leading coherent innovation ecosystem. In this regard it is important to learn from the past – for example with respect to AI and large technology companies – in allowing a small number of very large companies to dominate a sector, with all the associated challenges of security, governance and resourcing that that can create. This means, among other considerations, the need to balance the needs of large incumbent corporations against the challenges for specialised SMEs. Participation in the sector demonstrates not just government confidence in the value of UK expertise, but also ensures that the UK retains the skills of those working in it, offers reassurance to other investors, and provides opportunities for soft governance techniques that can ensure responsible innovation approaches are embedded throughout. Such an investment strategy would need to be both granular and detailed to provide support of the appropriate kind at various levels.

Horizon planning, not scanning

Exercises in trying to anticipate the future, often known as horizon-scanning, may be of limited usefulness in fast-moving sectors with many variables as there are too many uncertainties for it to be possible to create realistic predictions. However, a more proactive and constructive, anticipatory governance approach can plan and work towards particular outcomes whilst simultaneously retaining the capacity to respond to events. Currently the quantum computing sector is moving extremely fast, but it remains possible for proactive planning to steer its direction, for example, through choices around distribution of funding, prioritisation, decisions around export licences and so on. This need to make active choices about a future that is being planned for and worked towards goes beyond simple horizon-scanning about what may be approaching and is best implemented at a policy level.

Stakeholder input

The potential importance of the quantum computing sector to the UK economy, as well as the potential impacts in terms of (for example) security, makes it imperative to incorporate as many different viewpoints as possible into any policy approach. The challenges of financing small quantum start-ups, for example, may be rendered significantly greater by the exigencies of the National Security and Investment Bill – however, the security concerns that led to the genesis of the Bill are also significant. These are balances and trade-offs that have implications for trusted and responsible innovation approaches because – as previously discussed – 'soft' governance such as RI is more agile, has greater adaptability, and can encompass areas of action that are difficult to incorporate into legislation. There is, therefore, a clear need to incorporate multiple stakeholder viewpoints and needs into governance. This is a task that would be regarded as a priority for the RI Hub.

International viewpoint

In particular, the UK must participate in global discussions on quantum governance, which should not be limited to the creation of a level playing field in industry or definitions of terms. Given the global, systemic nature of both hard infrastructure such as internet communications and soft infrastructure such as financial markets, no single entity, whether a government or a company, should be 'setting the pace' of governance. The UK has an opportunity to lead on anticipatory governance for quantum – and given the size of the UK programme and its potential significance, it is vital to hear from diverse voices to ensure that the UK response brings societies and communities along with it.

Conclusions

As quantum computing emerges from the laboratory to become a potentially disruptive and transformational technology in a number or fields, a Responsible Innovation approach is increasingly urgent if the benefits are to be maximised and any social challenges are to be anticipated and addressed. We propose a Responsible Innovation Hub for Quantum Computing, a small but adequately resourced centre of expertise to catalyse RI awareness and activity in ongoing research and in the emerging QC innovation community. We envisage working closely with the National Quantum Computing Centre, alongside the Quantum Computing and Simulation Hub, as key actors in the UK QC ecosystem.

Responsible Innovation aims not only to meet societal challenges but, as a resource for creative thinking, to lead to the development of innovations and technologies that are likely to be embraced by the public and enjoy greater commercial success, and to maintain the UK's world-leading position in the emerging multi-billion-point quantum computing market while strengthening international research and co-operation.

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