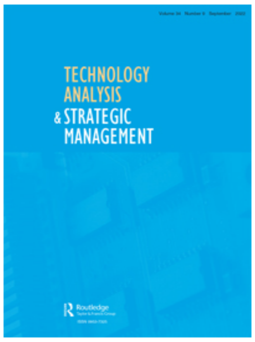

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Reading the road: challenges and opportunities on the path to responsible innovation in quantum computing

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ABSTRACT

Novel technologies such as quantum computing present new opportunities to support societal needs, but societal engagement is vital to secure public trust. Quantum computing technologies are at a pivotal point in their journey from foundational research to deployment, creating a moment for society to investigate, reflect, and consult on their implications. Responsible Innovation (RI) is one method for considering impacts, engaging with societal needs, reflecting on any concerns, and influencing the trajectory of the innovation in response. This paper draws on the empirical work of the RI team embedded in the Networked Quantum Information Technologies Hub. The team investigated researchers' perceptions of RI and their understanding of societal impacts of quantum technologies, and sought to gauge the challenges of embedding RI across a multi-disciplinary, large-scale enterprise such as the UK quantum programme. The work demonstrated some of the difficulties involved in embedding RI approaches, and in creating a dialogue between innovators and societies. Finally, the authors offer recommendations to policymakers, researchers, and industrial organisations, for better practice in responsible quantum computing, and to ensure that societal considerations are discussed alongside commercial motivations. Applying RI to quantum computing at this pivotal point has implications for RI in other emerging technologies.

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1. Introduction

The social, legal, economic, and practical landscape of quantum computing is changing fast. Advances and breakthroughs that five years ago seemed relatively remote are now discussed as imminent possibilities (e.g. Cookson 2021; Waters 2021). Although it is difficult to identify the precise 'tipping point'[1] of a technology whilst it develops, there is now increasing research, development, and investment in quantum computing – examples include: the development of Noisy, Intermediate-Scale Quantum Computing (Preskill 2018); investment by major corporations (Castellanos 2021); and the announcement of so-called 'quantum supremacy' (Arute et al. 2019).

Digital systems such as quantum computing can work to support the needs of society; many innovations have potential benefits for societies and individuals. However, technology can also have outcomes that do not benefit all of society – therefore, innovations that potentially impact societies in profound ways should have questions asked of them through the innovation lifecycle – questions such as: *who benefits? who's in control?* (Stilgoe 2013).

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Technologies such as quantum computing are highly likely to develop as just such impactful innovations that can affect society in significant ways (Inglesant, Hartswood, and Jirotka 2016). The process of such influential innovations moving from the research laboratory into practical use provides society with a 'window' during which technologies can be interrogated on questions around societal impact. It is therefore important that during this trajectory of development and deployment, issues concerning risks, responses, and responsibilities should be investigated. As use-cases become clearer there are opportunities to review possible effects that may raise concerns, and potentially to alter the trajectory of development and innovation, ensure accountability, and consolidate the rights of individuals and communities. If such opportunities are ignored, they may not recur until the technology is embedded in everyday use and potentially undesirable effects have occurred.

This paper draws on the empirical work carried out by the Responsible Innovation (RI)[2] initiative within the UK Quantum Technology Hubs. This work examined challenges and opportunities in using anticipatory, prospective approaches such as RI to help secure societally responsive quantum technologies in the UK. Section 2 briefly outlines the history of RI and its embedding into funders and funding calls, as well as why we consider the concept of 'quantum ethics' to be a necessary foundational component, but operationally insufficient. In Section 3, we outline the genesis of the quantum Hubs and the RI work carried out in them, before setting out some of our key findings from the work in Section 4. In Section 5, we discuss our findings, and suggest better practices for responsible quantum computing, and pathways to explore in the future, before concluding with Section 6.

2. Responsible innovation

The history of RI initiatives is now well-documented (e.g. Boenink and Kudina 2020; Owen et al. 2021). These initiatives emerged over a decade ago, with the aim of identifying and addressing uncertainties and risks associated with novel areas of research. They began in nanotechnology (Murphy 2010), expanded to geo-engineering (Stilgoe 2015) and synthetic biology (Frow and Calvert 2013), before widening to include computer science, robotics, informatics, and ICT more generally (Jirotka et al. 2017). A comprehensive definition 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. (RRI Tools n.d.)

In the UK, the Engineering and Physical Sciences Research Council (EPSRC) committed to RI across its portfolio of ICT research grants (Owen 2014). RI in this context has a number of dimensions, brought together by EPSRC in an interpretation known as the Anticipate-Reflect-Engage-Act (AREA) Framework (Stilgoe, Owen, and Macnaghten 2013). Since 2013, EPSRC has developed its commitment to embedding RI in funding calls. This commitment has been more emphatic at some times than others (Owen et al. 2021), but overall the trend is towards greater embedding of RI in UK research and innovation.

2.1. Embedding RI in UK funding; towards institutionalisation

Randles and Laasch (2016) describe 'institutionalisation' as a process of 'stabilisation of norms' (Randles and Laasch 2016, 54). They distinguish between formal adoption of such norms into policy and procedure (top-down), and a *de facto* process whereby behaviours are seen in practice regardless of 'official' procedures (ground-upwards). EPSRC as a locus for institutionalisation of RI in the UK, its promulgation of the AREA Framework, and inclusion of RI as a mandatory component of funding proposals (for example, Centres for Doctoral Training (EPSRC 2018)) indicate the top-down type of institutionalisation. Genus and Iskandarova (2018) critique the institutionalisation of

RI in the EU and US as 'partial', citing motivations for the inclusion of RI as rooted in 'the need to secure desirable outcomes from scientific research and promising innovations'.

However, a case study with interesting parallels for quantum technologies is to be found in Pansera et al. (2020)'s tracking of RI within a synthetic-biology research centre. Pansera et al. (2020) analysed some of the challenges of carrying out funder-embedded RI activities over the course of several years, arguing that with an essentially interpretive framework such as RI, it is critical to examine its operation 'in situated practice'. The researchers track a trajectory of understanding in the project's RI activity, beginning with a 'public engagement' conceptualisation based on 'deficit model' concepts (Wynne 1993) and shifting towards a much more 'deliberative and dialogic' approach, in a learning arc. Signs such as these are encouraging from an RI perspective; however, these developments may also be influenced by wider discussions in some fields of the ethical implications of novel technologies.

2.2. RI and 'quantum ethics'

Discussions of the ethical implications around technologies such as computing are not a new phenomenon – the comprehensive review by Stahl, Timmermans, and Mittelstadt (2016) of nearly 600 sources demonstrates roots dating back to the earliest computers – but have come to the fore again relatively recently in fields such as artificial intelligence (e.g. Leslie 2019). The concept of 'quantum ethics' has also recently appeared in the field (Khan 2021; Perrier 2021). These contributions often build on the ethical discourses of computing that, as noted above, have a deep history of questioning the impacts of these technologies.

These interesting contributions are necessary to foundational understandings of RI but are not sufficient; we argue that discussion of the ethics of quantum computing does not provide concrete guidance to the researchers and industrial start-ups grappling with the technical and engineering challenges of building a quantum computer. This is not to downplay the value or importance of drawing on ethical approaches, but the focus of a Responsible Innovation approach is based on the actions and day to day decisions of those working to create the technology (Pansera et al. 2020). Such an approach is rooted in ethics but has a very practical application. Ethics is necessary but not sufficient; it does not ask the questions that we believe must be embedded in the development of these technologies – *what will be the impacts on societies? who will benefit? And who will lose?*

3. Methodology

As part of the UK's national investment in a quantum technologies programme, four Hubs were funded for an initial five-year period starting in late 2014 totalling £270 m (EPSRC 2020). The Hubs were based in Birmingham, Oxford, York and Glasgow, and comprised large consortia of universities and companies. The aim was to exploit the potential of quantum science to develop technologies that would benefit UK business, government, and society (EPSRC 2020).

RI was incorporated into the entirety of the Quantum Technologies Programme and in the call for the Hubs from the outset. Each of the Hubs was required to commit to RI, though the means of doing this was left up to the leadership of each Hub. In three of the Hubs – echoing the synthetic biology case study discussed in 2.1 above – the RI work was largely framed as a type of public engagement or public communication and was carried out by the Hub's researchers. However, the quantum computing Hub included funding for an RI team within its proposal and consequently was able to sustain an RI effort throughout the five-year project. The work detailed below is therefore mainly focused on the work of the NQIT Hub – the project entitled NQIT-RRI.

3.1. Research methods

NQIT-RRI adopted qualitative methodologies to conduct the research; quantum technologies fields are interdisciplinary, highly specialised, and relatively small, meaning that qualitative work was judged to be more appropriate for the questions the research sought to investigate. What the project examined in depth was not just the state-of-the-art in technical terms 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.

It was clear from the outset that within the NQIT Hub, familiarity with RI methods was limited, and so a portion of the RI work was directed towards explaining and embedding RI approaches and working with developers to broaden their understanding of RI frameworks and methodologies. This included training (for example on ‘anticipatory’ techniques) so that developers and researchers were empowered to undertake this type of work themselves.

The research was multi-stranded, using interviews, case-study-focused workshops, and ultimately a series of ‘RI roadshows’ that used an ‘action research’ modality to demonstrate and disseminate the work around all four Hubs. The focus of the NQIT-RRI team was not to be responsible for all the RI activity in the Hubs, but rather to act as sources of expertise, generators of discussion, and facilitators of RI-focused conversations.

3.1.1. Strand 1: interviews

Semi-structured interviews were carried out with academic researchers at all levels in the programme, including directors of the NQIT Hub as well as researchers working directly in the laboratory and advanced theory, and with people from industry and companies related to the programme. These were an opportunity to hear views and in-depth opinions on the technologies, participants’ own approaches, and their views on how the innovations they were developing related to society. The semi-structured approach permits wide-ranging discussions that can investigate areas of particular interest in depth, while retaining the structure of a parallel set of questions for each participant, enabling comparative analysis.

3.1.2. Strand 2: case studies

Case studies were designed on the basis of the interviews and used as the focus for workshops and further interviews. The workshops and interviews encouraged broad-ranging discussions between co-researchers and developers, who in many cases may have been considering some of the questions for the first time. Drawing-together of specialists from different fields in workshops generated productive and creative analysis and insight around potential challenges and impacts from technologies.

The case studies developed analyses of particular use-cases where quantum technologies were identified by researchers and other stakeholders as particular areas of expected future application. These case studies investigated quantum for machine learning, and for defence and national security.

3.1.2.1. Case study 1. Quantum machine learning. The prospect of Quantum Machine-Learning (QML) has been widely discussed by researchers at the Hubs and in literature as an emerging field of research for quantum computing (Biamonte et al. 2018). The ability to parse large numbers of variables and vast quantities of data in relatively short timeframes or in ways which are otherwise intractable might enable applications for ML that could be highly commercialisable or help to solve important social challenges. For RI, questions around such a use case include:

(1) Skills shortages, because expertise-overlaps between ML and quantum technologies are rare.
(2) The difficulties of carrying out academic work in such an interdisciplinary area; this emerging field of research has, so far, been dominated by quantum experts, raising the risk that quantum methods for ML will lag behind the fast-changing applications of classical ML.
(3) Quantum is unlikely to replace classical-computing ML but may be complementary to it. However, the emergence of ‘quantum ML’ as a distinct field may divide ML between methods that are amenable to quantum and those that are not.

(4) Clearly, if quantum computing were to enlarge significantly the range or scale of ML, this could expand the already large societal impact of these technologies. But at the same time, there remains uncertainty about the viability and timescale.
(5) Responsible use of language to discourage hype. Many of the suggested techniques for quantum ML are years from achievement; however, some more generally applicable quantum computing methods for optimisation may be achievable sooner.

The discussions and literature review generated by the case study found that there is a large theoretical base to this emerging field of interest, but still a great deal of uncertainty about timescales and when, if at all, it will be implemented at scale for real-world applications. Perhaps, for this reason, there was a reluctance to engage with possible impacts and meanings – QML remains very theoretical and anticipatory work can seem remote from the day-to-day technical challenges.

The interdisciplinary nature of QML research is also a challenge for applying RI. The point around the responsible use of language in order to manage expectations shows an awareness of the need to represent quantum technologies carefully and in a non-hyperbolic way to stakeholders, which includes funders and policymakers as well as general publics. However, as classical ML demonstrates, real-world impacts and ethical challenges can be highly significant, and so QML should be the subject of focused reflection in order to try to address some of the problematic impacts, which may be extensions or entirely different from those seen in classical ML (e.g. Edwards and Veale 2017).

The QML case study, with its highly theoretical focus, served as a useful contrast with the second study, which examined the possible impacts on defence and national security.

3.1.2.2. Case study 2. Defence and national security. The investigatory workshop on responsible innovation in quantum technologies applied to defence and national security drew out themes and issues around dual-use, bad actors, state investment, and other issues. This is a field in which quantum technologies more broadly, as well as quantum computing specifically, are of interest for applications including quantum-enhanced navigation, sensing, imaging, and quantum secure communications. Although many of the potential applications remain theoretical in practice, their possible impacts were more readily discerned due to the already anticipatory modality of much defence work. Presentations voiced challenges from perspectives related to international relations, government, and RI. The discussions focused on:

(1) Whether the challenges raised by quantum technology are in some way different from those of other technologies; are their capabilities qualitatively different, or incremental improvements to existing functionality?
(2) Ethical challenges specific to quantum technologies – including the potential use of quantum technologies by terrorists, the enhanced encryption capabilities, and the potential violations of privacy.
(3) Responsible use of language to prevent a build-up of hype around quantum technologies.
(4) Potential regulatory frameworks.
(5) The importance of public dialogue, to learn the public's hopes and fears and to balance overstated or incorrect claims.

RI was identified as an opportunity for the research community to imagine possible and desirable futures together with different stakeholders. Overall, the workshop demonstrated that there is demand for a more structured conversation at the intersection of responsible research and innovation, quantum technologies, and the national security and defence sectors.

As with the QML case study, responsible use of language also appears here as necessary for keeping expectations at a realistic level. This awareness of the field's responsibility to stakeholders can be regarded as *de facto* RI, discussed further in Finding 5 below. The role of public engagement will also be discussed at greater length in Section 4. Both workshops formed part of the RI fieldwork that was made available to all the Hubs.

3.1.3. Strand 3: roadshows

The RI work in the NQIT Hub was significantly different from the RI approaches of the other three Hubs, so the NQIT-RRI team created 'Roadshows' – workshops at each of the Hubs, covering quantum imaging, quantum sensing, and quantum communications, as well as quantum computing – to demonstrate the NQIT RI work, generate greater awareness of, and discussion around, RI, and disseminate some of their findings. The Roadshows were productive of useful insights into the RI approaches in the other Hubs, as well as aiming to encourage adoption of the NQIT vision of RI around the other Hubs and to establish a collective RI strategy that could build on the commonalities between the technologies and activities of the Hubs.

3.1.4. Strand 4: public dialogue

A key aspect of RI approaches is engagement with stakeholders, and this was a core focus of the RI work in all the Hubs. However, there was very little previous data on public views, understanding, and attitudes to quantum technologies. A report by 'Sciencewise' in 2014, timed to coincide with the start of the first phase of the quantum technologies programme, was unable to find any direct data on public opinion about quantum technologies and instead drew its evidence from media reports and blog entries (Sciencewise 2014).

EPSRC, therefore, commissioned a one-off public dialogue exercise to create a two-way process of engagement by opening a channel between the public and experts/researchers, in order to:

- inform the public about the technology, services and devices which may emerge from the UKNQTP and the wider community;
- inform the quantum research community of the public's views (through the dialogue and its outputs) about the social and ethical implications of quantum research and technologies.

Participants were recruited from around the UK to represent a mix of participants in terms of gender, ethnicity, age, and background, around 25 in each of the locations of the Hubs and were paid for their time.

4. Results

The NQIT-RRI work threw into relief the challenges and opportunities that lie ahead for the development of responsible quantum technologies. RI within ICT fields requires interdisciplinary understandings, and utilising methods that may be entirely unfamiliar to physicists and mathematicians, therefore deepening familiarity with these methods formed a significant part of the work, as explained in Section 3.1 above.

The data collected through the various strands outlined in Section 3.1 was gathered into NVivo qualitative analysis software[3] and analysed inductively to discern trends and themes (Braun and Clarke 2006). The results detailed in Sections 4.1–4.6 below represent some of the key themes that emerged from the interviews, workshops, public dialogue, and roadshows.

4.1. Finding 1: public engagement considerations

Prior to the Kantar public dialogue (EPSRC 2017), there was very little evidence of public views on quantum technologies. The dialogue found wide familiarity with the term 'quantum' but little knowledge about what that meant in practice. Participants were – unsurprisingly – positive about the potential upsides of quantum technologies, particularly in healthcare and humanitarian fields, while also being concerned about potential misuse of these technologies. Their most significant concerns related to the broader and less predictable aspects of the rollout of quantum technologies, including: uneven access to the technologies; quantum as a profit-driven exercise at the expense of the public interest; and possible job losses from automation.

Participants in the NQIT-RRI interviews had different levels of experience with public engagement. There were some, particularly at the more foundational end of the research spectrum, who displayed scepticism about the value of explaining quantum processes so that non-specialists could form an educated view.

> it would be a mistake to imagine that … even a very alert and engaged individual is in a position to contribute … thoughts about the … direction a researcher can go in, because you are just ultra-simplifying things … so that they can make decisions. LD3

However, echoing Pansera et al. (2020), more often there was agreement that researchers had frequently been surprised by the level of self-education and interest among the general public.

> they're often coming up with detailed high-tech questions because they already know about … programming or computers or quantum … and often they're surprisingly interested in the details. LS1

> It's amazing actually how big the general population's appetite for popular science is and how well informed many of them are. LS3

In particular, several interviewees wanted more public engagement at earlier stages of education. They expressed frustration that basic quantum physics is not included in the National Curriculum and students commence their University courses with no quantum grounding.

> One of the big problems is that … even though quantum physics is more than 100 years old, schoolchildren don't learn about it. LI1

> These are absolutely basic concepts in the quantum world and students who have got to age 18 or 19 … don't know them. LS8

There was also understanding of the role of public engagement as creating a connection between science and society, and the resultant impact on society's ability to make broad decisions about how science and innovation should be directed.

> if you're working on that thing which might … change society, … the duty is … for a sort of communication from researchers to the wider public, so that everyone can then discuss that thing. LS9

4.2. Finding 2: policy drivers and routes to action

A clear finding from the Roadshows and interviews was a need to broaden the pathways between research and policy, and create more accessible tracks for both sides. Currently, consultation mechanisms most frequently draw on the expertise of very senior academics, who are often invited to give evidence to parliamentary groups and sit on panels.

> as scientists reach a more senior stage in their career they're more and more likely to be involved in committees and panels … and those committees and panels feed into the decision-making processes, along with political views and so on. LD4

However, not only may these views represent just a fraction of the views of the project, but they will inevitably be 'filtered' through a number of competing priorities. Individual scientists, or the project as a group, may perceive wider policy implications from their research, but there is currently no easy mechanism for passing these insights to research policymakers who would be able to act on them. An example is the need identified in the section above for quantum to be taught as part of the UK's National Curriculum – at present, the routes for researchers to pass insights such as these back into policy-formation mechanisms are weak and un-coordinated, so important perceptions may be entirely lost or insufficiently weighted.

4.3. Finding 3: the (non-)neutrality of technology

Our findings here support conclusions from *A Framework for Responsible Research and Innovation in ICT* (FRRIICT) (Jirotka et al. 2017), which found that several factors can combine to make it difficult for researchers to connect their work to societal impacts. The more foundational the research, and the further it is from applications, the less immediate is its ‘impact’. Researchers at this level often see their work as ‘neutral’ research, carried out for its intrinsic fascination. In NQIT-RRI we also found that researchers were more likely to be motivated by intense interest than by ultimate applications. There was a tendency to view end-uses as relatively divorced from the foundational research that had led to those uses – this led to a range of views on the responsibility to consider possible consequences.

> maybe I wouldn’t feel wholly responsible since … people … can do bad things with many things. LS4

> I’m building the device. So how it’s being used is a secondary question. LS6

The view of technology as necessarily ‘value-neutral’ in and of itself is frequently underpinned by years of training that promote this idea. At the same time, there is a dearth of input from interdisciplinary fields that might draw on wider or different perspectives that could be incorporated into the design of these innovations.[4]

However, we also found that – when equipped with the appropriate tools, such as training in RI – researchers do look forward and imagine possible futures, while accepting that future applications will emerge which cannot yet be predicted.

> that’s the continual lesson … how impossible it is to predict what’s going to make the … biggest changes to society. LS4

> we do talk, what is the best way to move forward and what would be the best mode of operation … these are important issues to discuss. LS5

RI work can also increase understandings of ‘who are stakeholders’ – for example, the concept of ‘stakeholders’ is not limited to ultimate users, and during early-stage development ‘stakeholders’ might be peers within the research team, or those in similar fields. RI training can increase these understandings.

4.4. Finding 4: the difficulty of anticipation

A further point to emerge from the discussions around stakeholders and the uses of technology is the challenge of identifying the appropriate juncture at which anticipatory work can be most effective.

> it’s so difficult to predict what effect basic research done now is going to have far in the future. LS1

Although an RI approach argues for a consistently anticipatory and reflective mindset, there are key decision-making points at which such activities become more than usually critical. Stilgoe, Owen, and Macnaghten (2013) discussed the use of ‘stage-gates’ in the development of technology. Stage-gates are built-in pause-points at which a technology under development should be reviewed to ensure it could pass through the gate to the next stage – but these key stages can also be difficult to identify in practice (e.g. Edwards et al. 2019). However, comments such as the quote above demonstrate that participants who may be unfamiliar with specific RI concepts are often articulating what may be termed *de facto* RI (Randles et al. 2016).

4.5. Finding 5: de facto RI

The concept of *de facto* RI is ‘in-practice’ behaviour that may not be framed as RI but that has the hallmarks of RI approaches, and is well-recognised (e.g. Lindner et al. 2016; Porcari et al. 2021). It was clear from the discussions with some participants that RI-type processes were familiar, even if they had not previously considered them as 'responsible innovation'.

> we need to communicate where … fundamental science impacts society. LS5

> we've identified something, what procedures should we put in place? LS3

> Almost every decision that is made has to have risk associated with it. LS8

These thoughts are well-aligned with such RI concepts as public engagement, anticipation, and reflection, respectively, but the next step is to draw these threads together more consciously into a cohesive set of considerations that inform each other and, ultimately, a response. These grassroots understandings align with the Randles and Laasch (2016) description of the 'ground-upwards' type of RI institutionalisation described in Section 2.1. Also in 2.1, at the other end of the RI institutionalisation scale are high-level 'top-down' questions of policy, which characterised the discussions around the nation-state impacts of quantum computing in Case Study 2 (Defence).

4.6. Finding 6: national and global impacts

A strong thread in the Defence Case Study was the potential impact on international politics and the balance of power globally, should one country develop scalable and error-corrected quantum computing before others (Inglesant, Jirotka, and Hartswood 2018). As one interview participant put it, 'whoever gets there last pays a price' (LS4). For example, if one nation or non-state actor was able to intercept encrypted Internet communications – a known possible application of quantum computing, albeit far beyond the capabilities of existing quantum computers – it would gain a strategic advantage and would probably not announce its capability (Schneier 2015)

Signs of national sensitivity around research in areas such as quantum computing are seen in protocols such as the UK's National Security And Investment Act,[5] which gives the UK government powers to investigate and potentially repudiate investment into a UK company for national security reasons. Such protectionist impulses – seen also in the multi-state Wassenaar Arrangement,[6] and the US's ITAR regulations[7] – can be understood as an expression of uncertainty around the global impact of novel technologies such as quantum computing. As our Defence workshop showed, there are multiple variables and high-level sensitivities influencing this space, and thus a need for a careful and measured approach. In Section 5, we draw this understanding together with our other findings to offer recommendations to policymakers, industrial organisations, and researchers.

5. Discussion and recommendations for practice

As outlined at the beginning of this paper, based on the numerous research strands of the NQIT-RRI project detailed in Section 3, we have identified several areas of challenge and opportunity for quantum computing as well as broader quantum-based technological development. We have developed these challenges and opportunities into recommendations for better practice.

5.1. R1: Create clearer, more direct pathways from researchers to policymakers

Informal pathways could provide appropriate mechanisms for researchers to express concerns or issues and for policymakers to access information from the 'coalface'. The absence of clear lines of communication between scientists and policymakers and guidance as to how to construct these dialogues in a mutually comprehensible way creates the 'filtration' effect described above in Section 4 (*Finding 2: Policy drivers and routes to action*). In this mode, an issue may be channelled through several layers of mediated intervention before it reaches a relevant recipient, by which time its immediacy and possibly matters of contextual significance may have been lost. In this respect, EPSRC, research councils and other funders can have an important role to play not only as motivators for RI but also potentially as intermediaries between researchers and policymakers.

5.2. R2: Generate more frequent, more detailed conversations with society

Public acceptance of quantum is unlikely to be smooth unless there are efforts to support consultation and two-way conversation – it is as important for researchers to listen to the public as it is for the public to learn about quantum technologies and therefore **increased public engagement is indicated**. The Kantar dialogue demonstrated that public understanding of quantum technologies is not keeping step with innovations in quantum fields. The public dialogue took place in 2017, and the pace of development in quantum has accelerated considerably since. This is also supported by the recognition from the case studies in defence and QML that projects and researchers have a responsibility to manage expectations through careful use of language and the avoidance of hype. There is not currently a high degree of knowledge in the public domain about quantum technologies and their possibilities – an **RI-driven public engagement programme**, aimed at addressing questions on governance, access, and other matters of public concern, would anticipate and pre-empt societal concern by engaging with citizens.

5.3. R3: Support interdisciplinary dialogue between fields to empower researchers

It is not reasonable to expect researchers to be able to apply techniques and methods from unfamiliar interdisciplinary fields without training, resourcing, and support. As quantum technologies move from the lab to the marketplace, **input from other disciplines becomes not only desirable but essential** to add richness of understanding to possible impacts. Lack of interdisciplinarity and support from more social-science grounded fields can create narrow views and definitions of 'success' within technological fields, as well as an attitude that technology is value-neutral. Presumptions around the limits of researcher responsibility create a hurdle that must be overcome when embedding more broad-based approaches such as RI. It is important to start these conversations early so that there is time and scope to influence trajectories where necessary. Ensuring access to such support will, therefore, be essential to ongoing RI work.

5.4. R4: Ensure wide, democratic access to technologies

De Wolf (2017) and others have suggested that inequity of access may well be a significant impact from quantum computing, and argue that **governments must ensure that citizens are able to access quantum computing** – that it must not be restricted to deep-pocketed corporations. There are broad political challenges for quantum technologies around questions of access: if states have access but deny it to citizens, what would this mean for the balance of power between the state and the individual? If corporations can analyse big data in new ways, will individuals demand tighter controls over their personal information? Market responses may also be seen – for instance, the access to AWS's Braket service[8] – that will influence these discussions.

5.5. R5: Participate in efforts for global co-operation

The 'national' approaches seen in the Defence workshop and discussed in interviews demonstrate an awareness that, although the UK has a depth of expertise in quantum technologies and in the application of RI techniques in quantum, there is nation-state level sensitivity to global competitiveness. This suggests a need to participate in worldwide discussion with partners and collaborators to ensure that **ethical concerns around fairness, access, and equity are not subsumed into technology arms races**.

5.6. R6: Expand the scope of responsible innovation

The application of RI within quantum fields is also an **opportunity to expand and verify the methodology of RI**, which is sometimes critiqued for being difficult to apply in real-world projects. This is a crucial moment as these technologies move from basic research into industrial application. The questions identified in this project, such as the precise timing of interventions – how 'upstream' is it reasonable to start looking at impacts? – can be further researched and field-tested. Additionally, the ongoing process of institutionalisation of RI can be further embedded in quantum technologies as understandings and practice mature.

5.7. R7: Widen the pool of stakeholders consulted

This is also an opportune time to **incorporate the views of wider groups of stakeholders**. There is a need to develop understanding, within all channels and levels of the policy-industry-academia model, of the possible effects and impacts of quantum-based technologies. As the work from Pansera et al. (2020) and our NQIT work has shown, not only are citizens and professionals able to bring insight and new perspectives to the research questions, but undertaking such dialogic activities can serve to mature RI understandings that in turn may inform the direction of the work. Good levels of understanding are currently restricted to relatively narrow groups and teams – engagement needs to happen not only with publics, but with all types of interested stakeholder including regulators, contingent industries, and other branches of the academy.

6. Conclusions

We have argued that we may be seeing a 'tipping point' for quantum computing, and that this is therefore an opportune moment to take a step back and reflect on what can be learned from the work of the NQIT-RRI project. Although the quantum technology Hubs varied in the readiness of the innovations they were investigating, these novel technologies are collectively at an important juncture in terms of both their ability to contribute to economic life and the need for a meaningful public conversation. Although to some degree quantum fields of enquiry and development have a 'blank sheet' in public perception, it is important to maintain this public acceptability, pre-empting the social and ethical challenges seen in other novel technological fields such as artificial intelligence. It was partly to that end that RI was included in the quantum technologies Hubs.

However, the RI work that was done in the Hubs is not complete (insofar as responsible development can ever be considered 'complete') and there is a need, identified throughout this research, not only for more granular understandings and embedding of RI concerns on a day-to-day basis, but also more in-depth policy responses that can provide an overarching structure to the development of the field. An infrastructure of 'responsibility' is required that understands the complexity of the landscape. RI can operate as both a 'top-down' structure and a 'bottom-up' methodology – seen in some of the 'de facto' RI work being carried out in the NQIT Hub – but there needs to be both an understanding and an overarching view of these different perspectives and levels of granularity.

Vermaas (2017)'s call for us to pay 'good attention' to these questions could be interpreted simply as 'close' attention but could also refer to the need for 'high-quality' attention, a call that we echo here. Although this call for a 'responsibility' infrastructure is a broader interpretation of RI than hitherto, it is our contention, based upon the NQIT-RRI work, that a narrow view of RI cannot be sufficient when incorporated into such a wide-ranging and potentially impactful field as quantum technologies. In order both to act responsibly and be seen to be acting responsibly, a cohesive and comprehensive approach is required.

Notes

1. Here used in a combination of the physics and sociological senses to indicate incremental changes that accumulate to then form a cascade beyond which there is no return to the former state.

2. RI and RRI are sometimes used interchangeably. In this paper we will use the former except where referring to the project name.
3. https://www.qsrinternational.com/nvivo-qualitative-data-analysis-software/home.
4. For example, Winner (1980) on whether artefacts can be inherently political.
5. https://www.legislation.gov.uk/ukpga/2021/25/contents/enacted.
6. https://en.wikipedia.org/wiki/Wassenaar_Arrangement.
7. https://en.wikipedia.org/wiki/International_Traffic_in_Arms_Regulations.
8. https://aws.amazon.com/braket/.

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References

Arute, F., K. Arya, R. Babbush, D. Bacon, J. C. Bardin, R. Barends, and J. M. Martinis. 2019. "Quantum Supremacy Using a Programmable Superconducting Processor." *Nature* 574 (7779): 505–510. doi:10.1038/s41586-019-1666-5.

Biamonte, J., P. Wittek, N. Pancotti, P. Rebentrost, N. Wiebe, and S. Lloyd. 2018. *Quantum Machine Learning*.

Boenink, M., and O. Kudina. 2020. "Values in Responsible Research and Innovation: From Entities to Practices." *Journal of Responsible Innovation* 7 (3): 450–470. doi:10.1080/23299460.2020.1806451.

Braun, V., and V. Clarke. 2006. "Using Thematic Analysis in Psychology." *Qualitative Research in Psychology* 3 (2): 77–101. doi:10.1191/1478088706qp063oa.

Castellanos, S. 2021. *Google Aims for Commercial-Grade Quantum Computer by 2029*. Accessed June 24, 2021, from https://www.wsj.com/articles/google-aims-for-commercial-grade-quantum-computer-by-2029-11621359156?mod=pls_whats_news_us_business_f.

Cookson, C. 2021. *PsiQuantum Expects Commercial Quantum Computer by 2025*. Accessed August 16, 2021, from https://www.ft.com/content/a5af3039-abbf-4b25-92e2-c40e5957c8cd.

De Wolf, R. 2017. "The Potential Impact of Quantum Computers on Society." *Ethics and Information Technology* 19: 271–276. doi:10.1007/s10676-017-9439-z.

Edwards, K., R. G. Cooper, T. Vedsmand, and G. Nardelli. 2019. "Evaluating the Agile-Stage-Gate Hybrid Model: Experiences from Three SME Manufacturing Firms." *International Journal of Innovation and Technology Management* 16: 8. doi:10.1142/S0219877019500482.

Edwards, L., and M. Veale. 2017. "Slave to the Algorithm? Why a Right to Explanation is Probably Not the Remedy You are Looking for." *SSRN Electronic Journal*. doi:10.2139/ssrn.2972855.

EPSRC. 2017. *Quantum Technologies Public Dialogue Report*. https://www.nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2018-07/Quantum Technologies Public Dialogue Full Report_0.pdf.

EPSRC. 2018. 2018 CDT Exercise – EPSRC Website. Accessed June 20, 2021, from https://epsrc.ukri.org/skills/students/centres/2018-cdt-exercise/.

EPSRC. 2020. UK National Quantum Technologies Programme. https://uknqt.epsrc.ac.uk/.

Frow, E., and J. Calvert. 2013. "Opening up the Future(s) of Synthetic Biology." *Futures* 48: 32–43. doi:10.1016/j.futures.2013.03.001.

Genus, A., and M. Iskandarova. 2018. “Responsible Innovation: Its Institutionalisation and a Critique.” *Technological Forecasting and Social Change* 128: 1–9. doi:10.1016/j.techfore.2017.09.029.

Inglesant, P., M. Hartswood, and M. Jirotka. 2016. *Thinking Ahead to a World with Quantum Computers the Landscape of Responsible Research and Innovation in Quantum Computing*.

Inglesant, P., M. Jirotka, and M. Hartswood. 2018. *Responsible Innovation in Quantum Technologies Applied to Defence and National Security*. https://nqit.ox.ac.uk/sites/www.nqit.ox.ac.uk/files/2018-11/Responsible Innovation in Quantum Technologies applied to Defence and National Security PDFNov18.pdf.

Jirotka, M., B. Grimpe, B. Stahl, G. Eden, and M. Hartswood. 2017. “Responsible Research and Innovation in the Digital Age.” *Communications of the ACM* 60 (5): 62–68. doi:10.1145/3064940.

Khan, I. 2021. Will Quantum Computers Truly Serve Humanity? Accessed March 15, 2021, from https://www.scientificamerican.com/article/will-quantum-computers-truly-serve-humanity/.

Leslie, D. 2019. *Understanding Artificial Intelligence Ethics and Safety: A Guide for the Responsible Design and Implementation of AI Systems in the Public Sector.* doi:10.5281/zenodo.3240529.

Lindner, R., S. Kuhlmann, S. Randles, B. Bedsted, G. Gorgoni, E. Griessler, and N. Mejlgaard. 2016. *Navigating Towards Shared Responsibility in Research and Innovation*.

Murphy, P. 2010. *Nanotechnology: Public Engagement with Health, Environmental and Social Issues. STRIVE Report (2007-FS-EH-1-M5)*. STRIVE Report Series No.61. Retrieved from www.epa.ie.

Owen, R. 2014. “The UK Engineering and Physical Sciences Research Council’s Commitment to a Framework for Responsible Innovation.” *Journal of Responsible Innovation* 1 (1): 113–117. doi:10.1080/23299460.2014.882065.

Owen, R., M. Pansera, P. Macnaghten, and S. Randles. 2021. “Organisational Institutionalisation of Responsible Innovation.” *Research Policy* 50 (1): 104132. doi:10.1016/j.respol.2020.104132.

Pansera, M., R. Owen, D. Meacham, and V. Kuh. 2020. “Embedding Responsible Innovation Within Synthetic Biology Research and Innovation: Insights from a UK Multi-Disciplinary Research Centre.” *Journal of Responsible Innovation*, 384–409. doi:10.1080/23299460.2020.1785678.

Perrier, E. 2021. *Ethical Quantum Computing: A Roadmap*. www.aaai.org.

Porcari, A., D. Pimponi, E. Borsella, P. Klaassen, M. Maia, and E. Mantovani. 2021. “Supporting RRI Uptake in Industry: A Qualitative and Multi-Criteria Approach to Analysing the Costs and Benefits of Implementation.” In *Assessment of Responsible Innovation: Methods and Practices*, edited by E. Yaghmaei, and I. van de Poel. Abingdon: Routledge.

Preskill, J. 2018. *Quantum Computing in the NISQ Era and Beyond*. https://doi.org/10.22331/q-2018-08-06-79.

Randles, S., and O. Laasch. 2016. “Theorising the Normative Business Model.” *Organization and Environment* 29 (1): 53–73. doi:10.1177/1086026615592934.

Randles, S., P. Laredo, A. Loconto, B. Walhout, and R. Lindner. 2016. “Framings and Frameworks: Six Grand Narratives of de facto RRI.” In *Navigating Towards Shared Responsibility in Research and Innovation: Approach, Process and Results of the Res-AGorA Project*, 31–36.

RRI Tools. n.d. Accessed March 22, 2021, from https://rri-tools.eu/.

Schneier, B. 2015. *NSA Plans for a Post-Quantum World*. Accessed June 24, 2021, from https://www.schneier.com/blog/archives/2015/08/nsa_plans_for_a.html.

Sciencewise. 2014. *Public Attitudes to Quantum Technology*. https://webarchive.nationalarchives.gov.uk/20170110123807/http://www.sciencewise-erc.org.uk/cms/public-attitudes-to-quantum-technology.

Stahl, B. C., J. Timmermans, and B. D. Mittelstadt. 2016. “The Ethics of Computing.” *ACM Computing Surveys* 48 (4): 1–38. doi:10.1145/2871196.

Stilgoe, J. 2013. “Why Responsible Innovation?” In *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, edited by R. Owen, J. R. Bessant, and M. Heintz, 306. Oxford: Wiley.

Stilgoe, J. 2015. *Experiment Earth: Responsible Innovation in Geoengineering*. Abingdon: Routledge.

Stilgoe, J., R. Owen, and P. Macnaghten. 2013. “Developing a Framework for Responsible Innovation.” *Research Policy* 42 (9): 1568–1580. doi:10.1016/j.respol.2013.05.008.

Vermaas, P. E. 2017. “The Societal Impact of the Emerging Quantum Technologies: A Renewed Urgency to Make Quantum Theory Understandable.” *Ethics and Information Technology* 19 (4): 241–246. doi:10.1007/s10676-017-9429-1.

Waters, R. 2021. *Goldman Sachs Predicts Quantum Computing 5 Years Away From Use in Markets*. Accessed August 16, 2021, from https://www.ft.com/content/bbff5dfd-caa3-4481-a111-c79f0d38d486.

Winner, L. 1980. “Do Artifacts Have Politics?” *Daedalus* 109 (1): 121–136.

Wynne, B. 1993. “Public Uptake of Science: A Case for Institutional Reflexivity.” *Public Understanding of Science* 2 (4): 321–337. doi:10.1088/0963-6625/2/4/003.