# RESPONSIBLE RESEARCH AND INNOVATION IN QUANTUM TECHNOLOGIES

A briefing note

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**Summary**

Quantum technologies (QTs) are a stated innovation priority of Government. Scientists are at an early stage of technological development, with substantial uncertainties, but there are high hopes for benefits – social as well as economic. At the same time, there are concerns that QTs may be negatively disruptive, introducing new risks and new ethical questions. Using the EPSRC Framework for Responsible innovation (https://www.epsrc.ac.uk/research/framework/), this briefing note outlines some of the issues that may be anticipated to arise from innovation in this area and outlines some suggested responses. The conclusion is that, while some challenges may be specific to the technical novelty of quantum technology, key public and stakeholder concerns are likely to centre on the technology's perceived beneficiaries. Important concerns about secrecy, surveillance, technological ownership and technological access can be anticipated. QT research funders and innovators should anticipate the intensification of a debate around QT and the need for a coherent response as activity grows.

**Introduction**

With their origins in the perplexing discoveries of quantum theory at the turn of the 20th century and their potentially revolutionary future applications, quantum technologies (QTs) can seem more appropriately the stuff of science fiction than real life. However, since the turn of this century, exploitation of the principles of quantum physics for technological ends has attracted growing private and public funding. True quantum computers may still be a thing of the future, but quantum technologies are already making a difference to communications, sensing and metrology.

As with previous disruptive emerging technologies, these applications have the potential for huge benefit, offering new economic opportunities as well as targeting societal challenges. But we can also begin to anticipate some of the dynamics that may influence the development of this area. This briefing note recognises that the ethical, social, and political concerns arising from this range of technologies will depend on the uses to which they are put. It outlines some of the emerging concerns that may come to be expressed by civil society and public groups. It is hard to distinguish at this stage which of these concerns arise from the defining features of the technology (unique to quantum) and which may be shared with other emerging technologies such as nanotechnology

This note is the product of a small research exercise, supported by the Engineering and Physical Sciences Research Council, to scope out aspects of Responsible Research and Innovation as they relate to QTs. It draws on desk research, a set of interviews and a roundtable workshop in March 2015, at which 17 attendees (stakeholders from industry, government, science and civil society) gathered to discuss RRI questions. This briefing considers two of the most prominent technologies emerging for in the short and long term – quantum secure communication and quantum computing (networked quantum information systems). It examines issues associated with these technologies and, drawing on ideas of responsible research and innovation, makes recommendations in response to such issues.

Responsible research and innovation (sometimes abbreviated to 'responsible innovation') is an approach, now adopted as a framework by EPSRC (https://www.epsrc.ac.uk/research/framework/), to understanding and governing emerging technologies. The EPSRC framework describes a responsible innovation approach as one that continuously seeks to *Anticipate*, *Engage*, *Reflect* and *Act* (AREA).

**Background**

Quantum physics studies subatomic particles, the smallest known building blocks in our universe. Many of our existing technologies, like microprocessors or lasers, rely on principles from quantum physics, although they do not harness these principles directly[1].

Quantum technologies (QTs) seek to harness quantum principles such as superposition and entanglement to achieve new functionalities. Quantum computers (QCs) offer to crack problems uncrackable, at speeds unreachable by conventional computers. Applications extend to calculating positions and interactions of atoms in large molecules with possibilities for drug development, analysing stock markets[2], designing new materials, developing self-driving cars, and resolving complex logistics problems[3]. **Quantum secure communication** uses more complex encryption to produce communication immune to hacking. This promises to increase consumer security, for example in online banking and shopping[5], and improve national security[4]. Other emerging QTs include **quantum metrology**, for more accurate methods and devices for measurement, and **quantum sensing** which would improve environmental monitoring, imaging technologies for healthcare, or subterranean mapping of fossil fuels[4].

**State of quantum technologies in the UK today:**

It is currently possible to identify different timeframes for the emergence of QTs in the UK, related to their diverse functionality and complexity. Some technologies, such as next generation atomic clocks and quantum secure communication systems (enabling accurate timing and navigation devices for defence, telecommunications, and finance industries) are either already in existence or are likely to be within five years. Additionally, according to the quantum technologies advisory board's most recent report[5] (March 23rd, 2015), we can expect to see the emergence of quantum sensor and imaging technologies for subsurface imaging (enabling better flood prediction, construction surveys and survivor-detection after earthquakes) in the next 10 years.

These technologies are typically presented as improvements on existing technological developments, and their 'quantumness' provides better, faster, cheaper options of these technologies. For example, one interviewee presented quantum key distribution (a form of quantum secure communication) in the following terms: '*once the key is generated [through QKD], their operational use is the same as current modes of use*'.

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[1] https://www.epsrc.ac.uk/research/ourportfolio/themes/quantumtech/

[2] Swann, A. (2012) 'UK scientists crack quantum computing', Computer Business Review, September 3rd, 2012. Available at: http://www.cbronline.com/news/uk-scientists-crack-quantum-computing-030812

[3] Hardy, N. (2013). 'Smart robots, driverless cars work – but they bring ethical issues too', *in The Guardian*, October 20th, 2013. Available at: http://www.theguardian.com/technology/2013/oct/20/artificial-intelligence-impact-lives

[4] Sciencewise (2014). *Public Attitudes to Quantum Technologies*. Available at: http://www.sciencewise-erc.org.uk/cms/public-attitudes-to-quantum-technology/

However, other technologies are predicted to emerge in the medium- to long-term (25 years and further). The recent QT Strategic Advisory Board report[5] proposes for example that commercial prototypes of quantum computers that enable solutions to problems that are prohibitively complex for current computer systems, such as large search and optimisation or the discovery and creation of new highly effective materials and medicines are likely to emerge beyond 2050. In the context of RRI for QTs – both the potential applications and the technology development path are unsettled and unknown.

**The social constitution of QTs**

Although these technologies are in their infancy, we can anticipate how interests and actors may come to shape what we can call a 'social constitution' for QTs. This is the set of conditions that are likely to shape public concerns about the emergence of this technology, in the same way as a set of political and ethical questions came to characterise the debate about genetically modified crops in the UK in the 1990s.[6] The political economy of QTs – who is seen as benefitting from research and development – will be a crucial determinant of public trust.

To date, the 'quantum industry' worldwide includes:

- Quantum components industry: those that make the pieces that enable quantum systems to exist e.g. Trevor Cross chief technology officer at e2v – UK firm that develops RF power, imaging and semiconductor technologies
- Quantum parts
- Few quantum systems (e.g. ID Quantique)

The potential military applications of quantum technologies were recognised early on by national defence actors. These potentials are embedded in the way the UK National Strategy for QT development is envisaged. The March 2015 report clearly identifies the defence sector as an early adopter of new and emerging quantum technologies.

Another factor is the uneven media coverage identified in the ETICA report[7]: not all emerging technologies in quantum are equally represented in the media/grey/academic literature on QTs. They find for instance that quantum computing or bioelectronics are severely under-reported on, whereas the ethical concerns raised by (long-term) developments in robotics, Artificial Intelligence, or Human-Machine Symbiosis are discussed in depth in both popular media and academic articles. This paradox was also noted during the workshop, where civil society representatives acknowledged that science-fiction provided a backdrop which draws public attention towards more futuristic-seeming enabled technologies.

**Emerging issues**

The March roundtable meeting of expert stakeholders flagged up four characteristics of the state of QTs today that are particularly important when thinking about responsibility, anticipation and action. These include the widely-held perception that quantum science is complex and difficult to understand; the difficulty to

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[5] Quantum Technologies Strategic Advisory Board (QT SAB) (2015) .'National Strategy for quantum technologies: A new era for the UK'. *UK National Quantum Technologies programme*. Available at: https://www.epsrc.ac.uk/newsevents/pubs/quantumtechstrategy/

[6] Grove-White, R., Macnaghten, P., Wynne, B., 2000. Wising Up: The Public and New Technologies. Centre for the Study of Environmental Change, Lancaster University, Lancaster Available at http://www.csec.lancs.ac.uk/docs/wising_upmacnaghten.pdf (accessed 20 June 2012).

[7] Heersmink, R.; van den Hoven, J. and Timmermans, J. (2014). Deliverable D.2.: Normative Issues Report. ETICA PROJECT. European Commission, Brussels: 7th Framework Programme. Available at: http://www.etica-project.eu/deliverable-files/Deliverable%202.2%20Normative%20Issues%20Report%2C%20final.pdf?attredirects=0&d=1

indisputably demonstrate the 'quantum-ness' of technologies; an existing conditional acceptance of less-widely-reported technologies (metrology, sensing, simulations, clocks); and the potential for disruption from harnessing news quantum principles, which may be over-hyped.

Roundtable participants noted that perceptions of the challenges and risks arising from quantum technologies into the future emerge against the backdrop of the GM controversies in the UK. A variety of challenges and risks arise from QT applications. Three are considered in more detail below. More broadly, the complexity of quantum behaviour generates concerns around the security and reliability of QTs[6]. Further, the inherent instability and high sensitivity of quantum states create challenges for the manufacture of these technologies[8]. This raises questions of affordability[4] and equitable distribution of costs and benefits (to date the only alleged quantum computer costs around $15,000,000[9]). Given that social needs, political priorities, and even ethical concerns change over time, designing an adaptive reflexive governance structure that can account for this pace-change is essential[10][11].

The recruitment of civil society representatives to the March workshop was particularly difficult, testifying to the general absence of QTs on current interest group agendas. This difficulty supports the observation that current discussions of the risks and benefits arising from emerging quantum science and technology is relatively non-existent[4], neither by researchers involved nor by 'publics' more broadly. Yet the types of issues that may arise from developments in this field can be characterised as both very high profile and sensitive issues. Questions of access, privacy, security, and general uncertainty about timelines, trajectories, and 'unknown unknowns' resonate.

### 1. Privacy

Privacy concerns are latent in contemporary technology developments, and QTs are no exception. Issues around unauthorised access, data corruption, hacking, and surveillance are the most conspicuous[6]. Quantum computing and secure communications provide an opportunity to develop new tools to guarantee privacy at both the individual and national level. However, developing QCs could generate the necessary computational power to hack most, if not all, contemporary encryption technologies[12]. This poses serious threats to private *(financial, for example)* data in the transitional phases while QCs coexist with classical computers[4].

### 2. Security

The communication security offered by quantum encryption is a double-edged sword: the 'uncrackability' of quantum-encrypted messages could increase the freedom of speech of citizens under authoritarian regimes.[13] At the same time containing the proliferation of unbreakable communication is of strategic importance to

[8] Aaronson, S. (2011). 'Quantum Computing New Insights, Not Just Supermachines', *in The New York Times*, December 5th, 2011. Available at: http://www.nytimes.com/2011/12/06/science/scott-aaronson-quantum-computing-promises-new-insights.html?pagewanted=all&_r=1&

[9] Shah, A. (2014). 'D-Wave prepping quantum computers to outperform conventional servers', *in PC World*, March 12th, 2014. Available at: http://www.pcworld.com/article/2107700/dwave-prepping-quantum-computers-to-outperform-conventional-servers.html

[10] Lawrie, G. (2011). 'Reflexive governance in biobanks: on the value of policy led approaches and the need to recognize the limits of law', *in Human Genetics*, 130(3): 347-356.

[11] Palmerini, E., Azzari, F., Battaglia, F., Bertolini, A., Carnevale, A., Carpaneto, J., et al. (2014). *Guidelines on Regulating Robotics*, 1–215.

[12] Shadbolt, P. (2014). 'Quantum Tech disappoints, but only because we don't get it', *in The Conversation*, July 15th, 2014. Available at: https://theconversation.com/quantum-tech-disappoints-but-only-because-we-dont-get-it-29229

[13] Heersmink et al., 2014

enable national security entities to prevent or solve crimes, particularly those involving non-state criminal networks or diffuse terrorist groups worldwide. The issue of security is further compounded by the current quantum cryptography 'Space Race', where governments in Europe and China are competing in the development of ground and satellite links to harness these anticipated technologies.[14]

Security concerns can be extended to include economic security at the national level. Interviewees highlighted how international military treaties – particularly the International Traffic in Arms Regulations (ITAR) – determine the way technology development is conducted in the UK. Specifically ITAR restricts that the exchange of US-generated information and materials pertaining to defence and military related technologies with non-US parties, including the UK. The list of restricted information and technologies changes over time. The implications of the US restricting the mobilisation of quantum knowledge protected by intellectual property rights on American soil, by British actors (industrial or military), pose a serious challenge to developing a UK QT critical mass. In response to this, the QT SAB report recommends that 'the UK quantum technologies community should be astutely aware of legislation with extra-territorial effect that could restrict the movement and sale of quantum products and service'.[5] Competing geopolitical interests suggest a convergence between national economic and military interests. Economic history suggests that the implications of technological monopolies have included failed innovation, and lock-in into sub-optimal development paths[15]. This concern was also expressed during an interview where one stakeholder interviewed commented that 'the best technology does not always win'.

### 3. Transparency

Private and public 'giants' dominate the research landscape, creating an aura of secrecy and complexity around QTs. For example, the research collaboration on QCs between the Universities Space Research Association, NASA and Google has not to date been engaged with public dialogue or questions of responsible research and innovation. This insulation from wider public engagement also raises issues of transparency, particularly in setting the agenda for research. This concern with transparency is made more complex in light of public (including scientific) perceptions of quantum physics as 'extremely difficult to understand' and 'difficult to indisputably demonstrate'[4]. From an RRI perspective, this research context poses a further challenge of how to include citizens in this field.

### 4. Hype

Emerging quantum science is a highly complex field, making visions of hype and doom difficult to scrutinise. QTs are presented as being semi-permanently on the horizon, and yet their emergence is unreliably reported. Indeed, media reports are disproportionately less likely to report on technologies that are either already in existence (quantum sensing for example) or will be in the next 5 to 10 years.

The interests of the quantum industry also rely on particular constructions of QTs as 'disruptive' technologies, adding value to existing technological systems. A correlated trend was expressed by a workshop stakeholder who argued that researchers tend to perceive claims of 'technological disruption' as a precondition for support and funding in emerging quantum science. These claims can be difficult to verify and often either do not fit the nature of the technology well, or may even prove to be incomplete or deceptive in the long-run.

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[14] Vallone, G.; Bacco, D.; Dequal, D.; Gaiarin, S.; Luceri, V.; Bianco, G.; Villoresi,P. (2014). 'The Space-Based Quantum Cryptography Race', in *The MIT Technology Review*. Available at: http://www.technologyreview.com/view/528671/the-space-based-quantum-cryptography-race/

[15] Nielsen, M. (2003). 'Simple Rules for a Complex Quantum World', *in Scientific American*, Special Issue 'The Edge of Physics', pp. 24-33. Available at: http://michaelnielsen.org/papers/SciAmSimpleRules.pdf

**The responsibilities of scientists**

The technical complexity of quantum physics and physicists' centrality to development and deployment grants them a privileged position in ongoing discussions about the regulation of QTs. Yet insofar as scientists work within moral and legal frameworks determined by society,  scientists are also citizens) and they share responsibilities for research *(as a public good)* and to society at large. If there is no 'pure technology'[16], and innovation pathways are affected by a range of *technical, social, political, ethical* and *legal* factors, then questions of values in QT development remain and scientists alone cannot provide complete answers.

To this extent, scientists may be seen as responsible for ensuring that scientific knowledge (and lack thereof) is honestly and openly communicated to society as a whole. In the words of interviewee 2 '*we need to be honest about what we know, but also what we don't know*'. Scientists should be expected to allow for and enable an dialogue which helps shape the further development of QTs. One interviewee argued that the 'onus is on [researchers] us to show people that quantum is better'. Finally, the governance of QT development should account for the inherent uncertainty of the scientific exercise, and particularly the limits of human foresight. Enabling the necessary dialogue will require both a supportive institutional setting and a new, more precautionary way of doing science.[17][18]

**Recommendations:**

Quantum research is still surrounded by uncertainty. QTs are emerging and therefore carry implications that are not regulated by current policies. Institutions engaged in QT R&D are encouraged to open up their research agendas and allow more public scrutiny. An open, reflexive discussion on the desirability of QTs and research prioritisation are a necessary stepping-stone for further research.

QTs entail fundamentally some new risks and opportunities.  Where past controversies around biotechnology have tended to converge around issues of contamination and human- or environmental-health effects, QTs challenge our understanding of the universe at a more fundamental level.  RRI – particularly its explicit focus on early action and anticipation – provides us with a new framework to tackle this novelty, and discuss issues of threats, responsibility, or ownership. At the same time we should remember that many lessons from past controversies will apply to emerging QTs. Some questions of the politics of science and technology are perennial.

A 'new language' for discussing QTs should be sensitive to the need to overcome the 'stereotype of quantum mechanics as extremely difficult to understand'[4] in order to promote as inclusive a debate as possible. Public engagement should represent a genuine attempt at fostering long-term, critical, thinking about innovation systems and the aims society wants QTs to support. Scientists and non-experts should be given the tools and capacity to generate a two-way discussion.

This difference in timing poses separate challenges to RRI for QTs. It is equally important to note that the first set of emerging technologies will not necessarily pave the way for the second set of QTs, and are best not considered as a proxy for understanding or anticipating future QT developments. It is important to consider that societal context is not fixed in time or space, and maybe influenced by, and simultaneously affect, the development pathways of QTs.

Answering some of the open questions raised by the development of QTs will require an early engagement with the social context in which these emerge. Commissioning, through Sciencewise for example, a public

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[16] Grunwald, A. (2005). Nanotechnology--a new field of ethical inquiry?, *in Science and Engineering Ethics*, *11*(2), 187–201.

[17] Jasanoff, S. (2007). Technologies of Humility. *Nature*, *450*(7166), 33. doi:10.1038/450033a

[18] Stirling, A. (2015). 'Towards Innovation Democracy? Participation, Responsibility and Precaution in Innovation Governance', STEPS Working Paper 78. Available at: http://steps-centre.org/publication/innovation-democracy-stirling/

dialogue exercise is a recommended first step. This recommendation is in line with Sciencewise's own recommendation that a starting point to future public dialogue relating to quantum technologies might want to consider the following question: 'What are the issues that quantum technology (and its applications) raise?'[4].

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