NQIT Networked Quantum Information Technologies

UK NATIONAL QUANTUM TECHNOLOGIES PROGRAMME

Thinking Ahead to a World with Quantum Computing

Key Points

Quantum computing, in its full sense, is still some years away

"Live" issues are about the narrative around quantum and uncertainties in when technologies will be available and what they will do

Issues on the horizon are about trust in the new technology and managing expectations

In the future, when quantum computers come online fully, issues are likely to be about who has ownership and control of them.

The NQIT project has responded to these challenges by engaging in a programme of Responsible Research and Innovation work.

This work has produced a **Landscape Report** and a set of **recommendations** to engage with stakeholders who will be affected by quantum computing.

Quantum technologies are advancing rapidly, in some cases already in the market, or becoming close to market. This brief focuses on developments towards quantum computing, which, in its full sense, is still some years from availability. In particular, we look at the Networked Quantum Information Technologies (NQIT) project, one of four research Hubs funded as part of the UK National Quantum Technologies Programme.

The brief looks at areas of interest and potential challenges in quantum computing that are "live", on the horizon, and that may arise in the future.

To meet these challenges, we propose a framework for Responsible Research and Innovation (RRI) and make recommendations for research programmes such as NQIT to take a leadership role in the narratives surrounding quantum, build public trust in quantum technologies and embed and implement RRI throughout the research programme.

Background to Responsible Research and Innovation in Quantum Technologies

Quantum computing is emerging in a society in which technology already plays an increasing role in our "digitally hybrid" lives. The eventual outcomes of innovation are hard to predict, and may entail unwanted and unanticipated side effects. The lessons of earlier technologies may provide some pointers to ways in which quantum technologies will interact with, and possibly exacerbate, existing socio-technical trends. At the same time, quantum is comparable to other powerful technologies harnessing the fundamental fabrics of nature - genetic modification, nanotechnology, and synthetic biology - which may raise fears of serious and irreversible consequences.

Embedding RRI in research and innovation projects is increasingly encouraged by funders, and particularly by EPSRC, and is an integral part of the UK National Quantum Technologies Programme. EPSRC has adopted the AREA Framework as a practical way to implement RRI:

- **Anticipate** the impacts
- **Reflect** on the motivations for the research, and social transformations these may bring
- **Engage** in inclusive dialogue and debate
- **Act** responsively where appropriate.

The AREA framework provides a foundation for a more tailored, domain-specific framework for RRI in research programmes such as NQIT. In developing this framework, we suggest the following **general principles**, which will guide us in refining practices of RRI throughout the lifetime of the programme. These principles are not necessarily specific to quantum technologies but are drawn from our early RRI research in NQIT and work with the other Quantum Technology Hubs.

What is Responsible Research and Innovation?

Responsible Research and Innovation (RRI) promotes research and innovation which is socially desirable and undertaken in the public interest.

It aims to stimulate creativity in science and the innovation arising from it, and ultimately lead to products and services that are more likely to be accepted by the public.

- All researchers should have the opportunity to engage in RRI related activities and the support to do so. Supporting the broadest possible engagement will embed RRI more deeply throughout the programme, and through all levels of the hierarchy.
- RRI should be thought of as a network of interconnected responsibilities that are distributed across various groups of stakeholders, not all on the shoulders of scientists. Partnerships with social scientists can help to understand how science and society interact; RRI specialists act as facilitators, with enough technical knowledge to initiate and coordinate RRI activities.
- An RRI framework has to span science and research activities, communication, commercialisation pathways, policy formation and funding directions, reaching across the research and innovation ecosystem.
- Liaison across research programes will enable each programme to benefit from the experiences of others. Many of the issues may be common, others are specific, and the comparison will yield useful insights. For example, a cross-Hub strategy for the UK National Quantum Technology Programme would maximise the impact and minimise duplication of effort.
- A commitment to RRI raises complex issues about the responsibilities of scientists, but a concern for responsibility should strengthen the quality of research. RRI is not set of additional activities added-on, but a potential resource for creative thinking and adaptation, aiming to embed responsibility in good scientific practice.
- Dialogue with the public, with early adopters, with civil society, and other stakeholders is crucial to ensure that the research delivers results which will be widely recognised and welcomed. Public communication exercises should aim to encourage dialogue, in specifically tailored activities such as workshops, and also in outreach events of all kinds.
- The RRI framework in its own turn must follow the precepts of responsible research, continually evolving, reflective and responsive to changes in technology and society and incorporating new insights.

AREA Framework for implementing Reponsible Research and Innovation

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Responsible Research and Innovation Challenges in Quantum Computing

Live, immediate issues relate to perceptions and the nature of quantum computing and quantum as a whole, rather than being focussed on specific applications.

1. **The uncertainties associated with realising quantum computing**
   Scientists and practitioners are still not able to be certain of the timescale for the engineering challenges to be overcome, what the capabilities of quantum computers will be, and ultimately what applications and social implications these will lead to.
2. **The character of quantum computing**
   Quantum computing is not strictly analogous to classical computing, but rather has a very specific mode of operation. We know that quantum computing will be able to solve some problems which are intractable for classical computers, but also that there are other problems which it will not solve. Its capabilities may be misunderstood or exaggerated.
3. **How we can talk about Quantum?**
   Is the easily-misunderstood quantum "spookiness", and "spooky action at a distance" from Einstein still useful? Is there a risk of negative perceptions of quantum?

The overarching theme is the narratives and discourses which surround quantum computing; narratives around uncertainty and the still-uncertain character of quantum computing combined with older narratives about quantum as strange and hard to understand.

Issues on the horizon revolve around areas of active research. The timescale stretches from computing-related technologies already starting to appear (for example, Quantum Key Distribution), technologies a few years downstream (for example, quantum simulation), to decades before the implementation of Shor's algorithm, a method of integer factorisation.

1. **Strong claims for quantum technologies**
   The laws of quantum mechanics can in principle be harnessed to provide theoretically unbreakable communications, truly random numbers, or perfectly trusted forms of computation. But implementation and engineering challenges limit these "strong guarantees" in practice. Shor's algorithm would render public-key cryptography schemes such as RSA insecure; but "post-quantum" cryptography is already an active area of research to overcome this threat.
2. **Verification**
   How do we know that the results are correct, if quantum computing performs functions which cannot be replicated classically? How can the "quantumness" of non-universal quantum computers such as D-Wave be verified? These and related questions, which are actively being addressed by theoretical and experimental research, could give rise to public misunderstanding.
3. **Other medium-term applications**
   NQIT has work packages in areas such as sensors, sensor nets, and quantum simulation. While not quantum computing per se, these are already emerging as the first direct applications of computation and computing-related quantum. These show the real progress which is being made, and, in applications such hyper-accurate navigation or for new mobile applications, have implications relevant to RRI such as privacy.

The overarching theme across these issues is the need to trust quantum computing and quantum technologies on a number of levels. Potential users and indirect users of quantum computers are affected by the outcomes but unable to verify results, and may even not be aware of the implications of quantum technologies in deriving them.

Future challenges will emerge as applications of quantum computing precipitate societal transformations. We cannot predict risks and controversies from entirely unexpected quarters, but we can continually anticipate and develop our sensitivities to the ways in which quantum computing may interact with existing trends.

1. **Machine learning in the context of an emerging 'algorithmic society'**
   Machine learning underlies many of the algorithms that play increasingly powerful roles in our society. What greater influence might be yielded by quantum-enhanced machine learning?
2. **Defence and national security**
   These sectors are likely to be early adopters of quantum technologies, including computing. There are applications for secure communications, interception, and enhanced navigation and sensing. Differences between the capabilities of different countries could upset the delicate balance of geopolitics.
3. **Ownership and access to quantum technologies**
   Only large, state-level or very large corporations and research labs are likely to have the resources to operate quantum computers, at least for the foreseeable future. One effect may be to cement or increase imbalances of power between these powerful actors and ordinary consumers and citizens.

Each of these areas of social transformation raises implications for RRI. Algorithms and the "algorithmic society" have real-world implications (think about the power of a Google search); defence and national security applications may raise fears of surveillance and loss of privacy balanced against the need for protection against terrorist and criminal threats; the dominance of "Big Technology" and "Big Science" can create an aura of secrecy and may feed public disquiet.

Practical Actions

These are the activites that are already being carried out to practise Responsible Research & Innovation (RRI) in the Networked Quantum Information Technologies (NQIT Hub:

- interviews and workshops with project members
- review of quantum technology and related literature
- liaison with other Quantum Technology Hubs
- workshops and case studies on key issues
- engagement with industrial partners and other potential early adopters
- structured dialogue with the wider public
- engagement with civil society and other key communities
- risk assessment and technology assessment methods
- informal and formal structured foresight exercises

NQIT as End-to-End Research

In comparison with RRI in some other areas of science and technology, there has been less attention, to date, given to quantum technologies. The RRI work within NQIT will start to redress the balance and, as emerging technologies, quantum gives a new perspective to RRI. In addition, NQIT is end-to-end research, using cutting-edge science to build working systems. NQIT is working across disciplines: Physics, Materials Science, Engineering, and Computer Science. NQIT includes fundamental research but this is driven by the impetus for a working system; even the fundamental research will have social and ethical implications.

There are many uncertainties about how these innovative technologies will make their impact in practice, which makes it especially hard to implement RRI in NQIT and related programmes. **But RRI should not be framed as an "impossible" task such as predicting the future. RRI does not demand prediction, but anticipation – developing the capacity to think about what might happen, and to be prepared for future eventualities**. Looking forwards, we can reflect on how quantum computing may play into existing trends, controversies and opportunities, while keeping a balanced viewpoint.

RRI also builds on decades of research into the history of science and innovation. This research has shown that the path from science to innovation and impact on society is rarely simple and linear. Science moves mostly in incremental improvements and progresses alongside technological and social innovations. Indeed, the business-focussed User Engagement programme in NQIT is already looking ahead and identifying application areas, and we are in frequent dialogue with this programme to explore the implications of these application areas.

A Framework for Responsible Research and Innovation in Quantum Computing

The framework for RRI in NQIT is the outcome of the Landscape Report, whcih is available from the NQIT website:

http://bit.do/NQIT-RRI

This framework starts from the AREA framework but is attuned to NQIT. As a focussed project with a clear management structure, we, as RRI practitioners, are able to be quite specific in NQIT about the issue areas and the stakeholders; we can engage with stakeholders through events such as the project forum, and we can have a part in the outputs and make recommendations to the project leaders.

Although the framework is still a work in progress, the Landscape Document sets out a series of **practical actions** to be developed further but already taking place as we practise RRI in the Hub.

And in response to the framework, NQIT should be ready to act to:

- shape the direction of innovation, and to
- encourage responsibility as a part of professional research practice.

A timeline of quantum computing, with relevance to RRI, showing time periods and issues with an indication of areas of quantum research

Now

Active Areas of Quantum Research:

- Cryptography & QKD
- Abstraction Layer
- Ion traps

Immediately visible issues

Narratives around quantum computing:

- Uncertainty
- Character of quantum computing
- Quantum: "spooky and difficult"

Greatest uncertainty in quantum computing outcomes

Soon

- Photonics, memories & switches
- Atom-photon interfaces
- Quantum simulation
- Diamond & superconducting qubits
- Sensors & sensor nets
- Hybrid quantum-classical
- Ion-trap entanglement

Issues discernible on the horizon

Trust in quantum computing:

- Strong claims for quantum
- Verification
- Simulation & models
- Sensors, sensor nets

In the Future

- Blind quantum computing
- Universal comms nodes
- Crypt-analysis
- Machine learning & AI
- Fully scaleable quantum computing

Application areas of quantum computing

Transformations and quantum computing:

- An "algorithmic" society
- Defence & national security
- Ownership, loss of control by individuals

Least uncertainty in quantum computing outcomes

Recommendations

1. **Be honest about the uncertainties surrounding quantum technologies**
   At the same time find ways to articulate an informed understanding of what is likely to happen and when. There is a risk of a "fall from grace" if expectations are set too high; for example, in medical advances a time of 10 years is often suggested between the lab and a new treatment. Take public concerns seriously, to avoid any deep seated "quantum phobia" taking root.

2. **Find a way to talk about the specific character of quantum and quantum computing**
   Talk about both its powers and limitations, risks as well as benefits, as distinct from classical computing. This is an area ripe for misunderstanding – such as the notion that quantum computing can solve any problem currently too hard for a classical computer. When talking about quantum physics use "counter intuitive" as a much less loaded term than "spooky". Emphasise the effectiveness of quantum mechanics underpinning the engineering of existing everyday technologies such as lasers. It might be useful to explore ways in which an artist in residence can help to express complex scientific ideas; this has proven effective in other RRI projects.

3. **Work to ensure trust in quantum computing by the users and by third parties who rely on these results**
   Verification and discussions about the extent to which non-universal quantum computers are really "quantum" could raise unnecessary public concern; make sure that the verification work is not focussed solely on technical audiences, but reaches out to broader constituencies. Work towards demystifying quantum computing, including demonstrations of quantum computing capabilities in ways that are meaningful for broader audiences.

4. **RRI also embraces "de-facto" responsibility activities, including public engagement**
   These may not be labelled as such – this can include informal discussions with colleagues over coffee, quantum science as a cultural activity, and outreach through science events and the press. Current research to devise "post-quantum cryptography", overcoming the risks to existing cryptography from powerful quantum computing, is also a form of RRI, taking responsible action in advance of the threat. Often, it will not be a question of "doing things differently", but of maintaining an interested and aware attitude. It is likely that researchers are already practising RRI in this sense.

5. **Build capacity and join-up RRI activities**
   Skills for anticipation and reflection could be developed by self-directed study materials, workshops, posters, seminars, and structured foresight exercises. RRI activities should be connected together as part of a joined-up strategy, supported by an RRI community, "RRI Champions", drawn from researchers at all levels and people working in communications and technology transfer.

6. **Include RRI in the structure of research programmes**
   RRI will show the most benefits if it is supported by appropriate, well defined but flexible and not over-complex governance structures, working with the existing structures rather than imposing top-down regulation. Producing regular RRI reports for a project will, increasingly, identify substantive issues and may require a response from project management.

7. **Disseminate RRI through channels to influence research policy**
   We have identified a need for a more defined route to enable the findings of RRI to reach those who are in a position to act on them. These channels – acting upwards as well as downwards – could take a number of forms: a repository of issues, co-ordinated across the Hubs, would be a useful technical resource.

8. **Engage in dialogue with the public and stakeholders**
   This is not a new point but needs to be emphasised here. As well as interaction in public outreach, the kind of measured, interactive dialogue which will give a broader picture of the public perception of quantum technologies will require a wider pool of participants and a more structured approach.

Networked Quantum Information Computing (NQIT)

The Networked Quantum Information Technologies (NQIT) Hub is part of the UK National Quantum Technology Programme.

It is led by the University of Oxford and involves 9 UK universities and over 30 companies all working together to develop a quantum computer demonstrator and, in the process, realise an entirely new technology sector.

NQIT has responded to the risks and uncertainties of quantum information technology by engaging in a programme of Responsible Research and Innovation, led by Professor Marina Jirotka and Dr. Philip Inglesant in the interdisciplinary Human-Centred Computing group at the University of Oxford

This brief is a summary of the report, "**Thinking Ahead to a World with Quantum Computing: The Landscape of RRI in NQIT**", which is available to download on the NQIT website:

http://bit.do/NQIT-RRI