1. The following is a submission on behalf of the Networked Quantum Information Technologies Hub (NQIT). This is the largest of the four Hubs in the UK National Quantum Technology Programme, a £270 million investment by the UK government to establish a quantum technology industry in the UK. NQIT is working towards building a quantum computer demonstrator, the Q20:20 engine, which demonstrates a networked, hybrid light-matter approach to quantum information processing.

The NQIT Hub brings together teams in physics, engineering, materials and computing, from nine UK universities (Oxford, Bath, Cambridge, Edinburgh, Leeds, Southampton, Strathclyde, Sussex and Warwick) three government agencies and dozens of industrial collaborators.

It is led by the University of Oxford and the authors on behalf of NQIT are:

- Professor Ian Walmsley, Principal Investigator and NQIT Director
- Professor Dominic O’Brien, Co-Director for Systems Integration
- Evert Geurtsen, Co-Director for User Engagement

More details about the scope of the NQIT programme and its progress can be found on the NQIT website and the public NQIT reports:

- NQIT Annual Report 2017
- The Commercial Prospects for Quantum Computing
- Technical Roadmap for Fault-Tolerant Quantum Computing
- Thinking Ahead to a World with Quantum Computers

Links to each of these reports are listed in the appendix.

2. Statement of conflict of interest: All three authors are members and employees of the University of Oxford. Professor Walmsley and Professor O’Brien intend to become co-founders and shareholders of a forthcoming spinout company from the University of Oxford that will commercialise certain technologies developed in the NQIT programme.

3. About the opportunities and challenges for quantum technologies, and in particular quantum information and networking technologies, the views of NQIT are summarised as follows:

The UK Quantum Technologies Programme was well designed and is delivering world-leading research outcomes and industry and public engagement: “the Hubs - individually and together as a national network -, had demonstrated good progress towards their objectives at the mid-term stage, with no weaknesses identified” (from a letter dated 2 December 2016 from Dr Liam Blackwell, Quantum Technologies Theme Lead, EPSRC to the Directors of the Hubs). The UK has maintained its position among world leaders in this new technology field. To capitalise on this position, in the view of NQIT, the UK must commit to a continuation of the research programme and expansion of the commercialisation programme as per the recommendations of the Government Office for Science’s 2016 report. For quantum computing specifically this means:

- continuation of the UKQT Hub programme from 2019 through to 2024;
- the creation of a dedicated Innovation Centre of Quantum Computer;
- the commitment to build a National UK Quantum Computer.
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Together this will boost the already strong UK photonics industry, establish a new quantum information and networking systems industry and encourage application developers and users of quantum computing to congregate in the UK. Together they will build a new industry and create competitive advantages and productivity improvements for the existing UK industry and economy.

4. With respect to the terms of reference, the views on behalf of NQIT are as follows:
5. The progress that has been made on the recommendations in the Government Office for Science’s 2016 report;
5.1. The Government Office for Science’s 2016 report made 11 recommendations. Of those the following recommendations were of direct relevance to the NQIT Hub:
5.2. Recommendation 1: the research activities in the NQIT Hub is maintaining the UK world-leading position in the field of quantum information technologies (see below for further technical details). The User Engagement programme of the NQIT Hub already engages directly with Industry and in the pursuit of collaborative research a growing number of companies are making substantial contributions. In research these contributions are predominantly in kind, but UK investors have committed substantial cash investments in emerging spinouts and startups. In our opinion this indicates that, as a result of the UKQT programme and its inclusion of User Engagement activities, there is a willingness in industry to help accelerate commercialisation, now and in the future phases.
5.3. Recommendation 6: NQIT recognises that, working with all parts of the UK research community, we need to identify challenges which, if solved by a quantum computer or simulator, would have important benefits to government, business and citizens. To this end NQIT is making available early platforms for research and development of quantum computing and simulation. NQIT has reconfigured some of its activities to enable the creation of a unique emulator and is also working with 3rd parties to secure access for early users to the early-generation of quantum computers. NQIT has started to involve scientists in academia and in industry to become aware and, in due course, skilled in quantum computation. Within NQIT a new work package has been created that is dedicated to applications in Machine Learning.
5.4. Recommendation 10: NQIT has developed a vision for the next phase of the UKQT programme that goes beyond the scope of the current Quantum Technology Hubs and involve deeper involvement of industry alongside academic research. Furthermore, NQIT is helping to create new spinout ventures that enable access to commercial expertise and resources to consolidate the research outcomes into commercial products and services and accelerate the development of a quantum information technology industry in the UK.
6. The relative contribution/support from government, researchers and businesses needed to make quantum technologies a success;
6.1. Quantum computing is still in a stage that requires ongoing fundamental research. Industry in the enabling technologies (e.g. photonics) is willing to engage and invest but for systems, applications development and commercial use, there is neither an established industry nor a skills base yet. Investors are willing to contribute to the creation of this new sector but look to academia and the UKQT programme to provide the leadership, technological progress and skills development.
6.2. NQIT fully endorses the recommendations from the Government Office for Science’s 2016 report for Innovation Centres and accelerated commercialisation. NQIT believes that this approach will be successful only if, alongside the proposed Innovation Centre, the UKQT programmes continues the current technology Hub programme from 2019 to 2024 to ensure that a scientific research and technology programme can drive the component performance needed for fully scalable quantum computing. The Innovation Centre should have a mission to build or acquire the UK’s first quantum computer, and to develop on industry led applications for this machine, whilst the research-led Hubs continue to build on the UK’s scientific leadership that, in the immediate future, remains essential as a foundation for the applied development of technologies and engagement of new users and supply chains.

7. The current state of the UK quantum industry and its potential going forward, including particular strengths and challenges;
   7.1. The UKQT programme continues to be the focus of the emerging UK quantum industry. It provides leadership in setting the priorities for research and technology development and offers a clear focus for UK industry, investors, government and the public.
   7.2. The design of this programme combines the research from a multitude of academic institutions and includes the engagement of industry and public, skills development and responsible research and innovation (RRI) activities. The comprehensive nature of the programme allows for accelerated commercialisation and public adoption of a future industry and is itself a core strength, confirmed by the fact that other countries and organisations have adopted a similar comprehensive approach since (e.g. QuBiz in Denmark, QuTec in The Netherlands, the EU Flagship on Quantum and others).
   7.3. Research progress and results confirm, in our opinion, that the NQIT technology of a networked quantum computer has maintained its leading position. The NQIT ion trap, which is the technology at the heart of the NQIT quantum computer, offers the highest precision qubit in the world. The ion-trap nodes are connected together in a photonic network such to create a scalable quantum computer architecture and all technological challenges to build this network are being met by the research teams, often in collaboration with companies in the photonics industry. The technology that will be demonstrated at the conclusion of the NQIT Phase 1 programme will be scalable beyond the main competing technology, i.e. superconducting circuits, in terms of useable number of operations which is the decisive measure of usability.
   7.4. Alongside the main architecture, NQIT is also engaged in research using diamond as a material for quantum computing in the medium to long term. As with the photonic network technology (which also is used with the diamond-based nodes), the UK can demonstrate particular strengths in both academic research and in the established enabling industry.
   7.5. Aspects of superconducting-based quantum computers are also researched in NQIT, not least in acknowledgement of its competitive position based on the investments elsewhere. Major scientific progress has been achieved and in Oxford a new spinout has already been created with private investment.
   7.6. The investment community in the UK has been encouraged by the UKQT programme and the emergence of privately funded spinouts is evidence that this traditional UK strength is also engaging. Furthermore anecdotal evidence suggests that foreign companies’ activities in quantum technologies are engaging in the UK because of the programme (e.g. QxBranch, IBM Q).
7.7. Corporations engaged in research and technology in the UK are showing early interest in the applications for quantum computing and their interest is being channelled towards the early experimental platforms that are developed in or made available through the NQIT Hub.

7.8. In summary, the UK is building on its strengths in all aspects of innovation: authoritative research, investment and engagement with industry.

8. What oversight or regulation is needed;

8.1. NQIT reports to the Engineering and Physical Sciences Research Council (EPSRC) and its Quantum Technology Programme Operations Group (POG) and Strategic Advisory Board (SAB). The Quantum Technology POG focuses on the implementation of the UK National Quantum Technologies Programme, including coordination of efforts by the various government agencies and key organisations concerned with the development of Quantum Technologies in the UK. The SAB contains representation from EPSRC, Innovate UK, National Physical Laboratory (NPL), Defence Science and Technology Laboratory (DSTL), Government Communications Headquarters (GCHQ), Department for Business, Energy and Industrial Strategy (BEIS) and the Knowledge Transfer Network (KTN).

8.2. The Government Office for Science’s 2016 report recommends that regulation should not be a barrier to the use, deployment and commercialisation of quantum technologies but the National Programme should ensure that regulators and standards bodies are aware of the capabilities of the technologies under development. NQIT follows these recommendations already through a regular dialogue with the National Physical Laboratory and other members of the POG and SAB.

8.3. In the opinion of NQIT no immediate further measures are required for oversight or regulation.

9. Potential barriers for developing quantum technologies, and how these might be overcome;

9.1. To successfully develop scalable quantum information technologies and its applications we will need to:
   - continue to improve the fundamental scientific understanding specially to enable improvements in precision and speed of qubits and networks;
   - overcome a number of technological challenges, mostly in the field of engineering;
   - develop skills and resources (in industry) to consolidate research outcomes into scalable products;
   - develop the tools and skills to develop quantum computing applications;
   - encourage and support collaboration between researchers and industry and between diverse fields of science and diverse sectors in industry.

9.2. To overcome these challenges the UKQT programme will require continued leadership and access to resources and this should be considered in an international context.

9.3. Quantum technologies have been identified by many governments as a matter of national priority and by the established technology sector as both a large commercial opportunity but also a threat to their established interests. As a result, the international research activity has accelerated dramatically in recent years.

9.4. This acceleration results in more progress in research and technology but also is noticeable in the international competition for the best scientists, skilled researchers and engineers and industrial enablers and sponsors.

9.5. The farsighted UKQT programme has helped to maintain the scientific advantage of the UK and start the industrial engagement ahead of most other countries. However, to
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maintain that advantage and to eventually reap the rewards though commercialisation in all parts of the future value chain (supply, build, programme and use) the UK must continue its commitment to the UKQT programme into a second phase.

9.6. Anything that slows down the pace required to deliver leading NQIT platform and attract early users, suppliers, developers of applications, including allowing the fragmentation of research efforts; loss of leadership of the hubs may jeopardise the prospects of the UK quantum information industry.

10. What research priorities there should be for quantum technologies and their possible uses, and who is best placed to undertake/fund that work;

10.1. It is the opinion of NQIT, informed also by a recent EPSRC-organised consultation beyond the NQIT Hub, that the development and continuous improvement of scalable architectures and technologies should be the highest priority for the UKQT programme for quantum information technologies. This requires a continuous improvement of the precision and speed of the network nodes, overcoming the technological challenges in the node-connecting network and apply expertise to reduce costs, size, production- and installation-times and increase reliability and quality.

10.2. In the opinion of NQIT, and in consideration of the technological barriers mentioned above, that task is best undertaken by a Technology Hub with academic members. The Hub design has shown to deliver leadership that can effectively guide and control research activity so that they deliver outcomes that are both world-leading and relevant to the technology development programme. The Hub structure has also proven to be most adept at engaging with specialist companies to gain access to their expertise or to create spinout companies where such expertise does not yet exist but can be created with the resources from private investment.

10.3. A second critical priority is the development of skills, platforms and software tools to start the development of quantum information algorithms and applications. Such activities are already underway now within the NQIT Hub but in future it may be considered that such activity may be best undertaken in a dedicated setting for the promotion, training and facilitation of quantum information developers and users in academic science, government and industry. In our opinion facilitation should include the provision of a computing platform. Initially that may be an emulator, a 3rd party ‘noisy’ device or simulator but in due course should include access to a scalable UK National Quantum Computer of a design that has been developed in the UK and is supported by the UK quantum technology industry.

10.4. NQIT would wish to add one important cautionary note against the separation of the technology development and application development. Quantum information technologies and quantum computing are still in a very early stage and has not yet arrived at a maturity where application development can be understood without also a thorough understanding of the underlying physics and engineering science. It is also hard to see how an application developer in the UK would have any advantage over a developer elsewhere in the world unless he or she could benefit from the immediacy of the science and technology community that is creating the platform for the application. For this reason, the proposed continuation of the Technology Hubs and the creation of the new Innovation Centres should include close coordination between the two entities.

11. The role of international collaboration in quantum technology research and development; and the risks and opportunities of Brexit in this area;
11.1. In view of the rapidly escalating international demand there is a scarcity of experienced scientists, early career scientists and skilled engineers and technologists and these individuals traditionally are highly mobile. Hence the risks and opportunities of Brexit are predominantly those associated with decisions that either encourage or discourage individuals to work and settle in the UK.

11.2. The other important factor to attract the best scientists and most skilled technologists is a long-term funded research programme, broad participation and the prospect of an exciting emerging industry sector.

11.3. International collaborations and exchanges of people and information are an essential part of fundamental research. Nonetheless, as the technology moves towards commercialisation, intellectual property, know-how and expertise will become less accessible for those not involved in any particular piece of R&D activity, either direct or through formal agreement.

11.4. In our view, if the UK wishes to have first-hand access to research and innovation results elsewhere, it must have its own results in exchange. In other words, ongoing public funded research in the UK is an essential ingredient to international collaboration.

12. Any challenges from potential civil/military ‘dual-use’ applications of the technologies, and how these can be addressed;

12.1. It is still very early to assess the most likely applications for quantum information technologies but given the universality of computation inevitably there will be dual-use applications for quantum information technologies too. The current governance of the UKQT programme includes advisors from DSTL and GCHQ among others to whom we look to help recognise these matters and their implications on the actions within the Hub.

13. Any potential societal implications—positive and negative—of the development of quantum technologies, including on health, security, privacy or equality.

13.1. NQIT is conscious that its quantum technologies will have the potential to change our world profoundly. These changes may be hard to predict, as emerging technologies combine with existing technologies and markets in unexpected ways to lead to unexpected changes in economics, society and culture. It is for this reason that the NQIT programme includes an extensive Responsible Research and Innovation (RRI) programme to help identify such potential changes and impacts.

13.2. Quantum information technologies are predicted to give scientists and industry the tools to make new discoveries and develop new applications. Those may result in new medicines or materials, cleaner energy, more efficient infrastructures, more productive factories, safer cars etc. All these applications are as yet speculative, but history suggests that disruptive technology indeed creates new products and services that are socially desirable.

13.3. The UK is a large and attractive market and arguably these new products and services will become available in the UK irrespective of the UK role in creating the quantum information technology.

13.4. Therefore, a more important implication to consider is the opportunity to create an international competitive advantage for the industry in the UK. If the programme can maintain its international leadership and continues to be encouraged to engage with industry it can boost the supply industry, create new industries in the building and programming of quantum information systems. As a first mover and with a national
programme that includes engagement with a new application development community it will let the UK industry create competitive advantages with new and better products and services. The latter is also possible using the technology provided by technology companies from outside the UK but in that case, there is no reason why a UK company has any advantage over a company in any other part of the world.

14. At this time the UK has a leading position in research and industry engagement. To capitalise on this position and deliver a new industry, a competitive advantage to existing industry and create an economic and societal advantage, NQIT strongly supports the recommendations in the Government Office for Science’s 2016 report plus the proposals for a continuation of the UK Technology Hubs (including research and user engagement) through the next phase (2019 to 2024), the creation of Innovation Centre, to build a UK National Quantum Computer and support facility and the continued inclusion of quantum information technologies in the Industrial Strategy Challenge Fund.

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Appendix 1 – Links to NQIT Publications


The Commercial Prospects for Quantum Computing - http://nqit.ox.ac.uk/content/commercial-prospects-quantum-computing