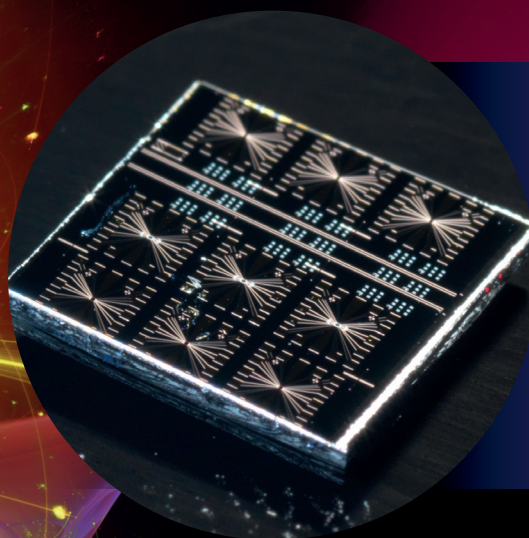


Quantum

Opportunities for
superconducting quantum
technology in the UK

OCTOBER 2018



Opportunities for superconducting quantum technology in the UK

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ABSTRACT

This report, coordinated by the superconducting quantum computing team at the UK National Physical Laboratory, summarises our view of the state of the art in superconducting quantum computing (SQC) and the real-life problems that this technology is likely to be able to tackle in the short term and over a longer perspective. It also analyses the scientific and engineering expertise, specialist facilities, and other resources for SQC readily available in the UK and those we are missing. Based on this analysis the paper makes a projection of what the country could realistically achieve in a ‘space race’ for quantum computing capability in different investment scenarios.

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EXECUTIVE SUMMARY

In a radical departure from classical computing based on digital bits taking a value of 0 OR 1, the quantum bits (qubits) of a quantum computer can simultaneously process bit values 0 AND 1. Using this capability, multiple interacting qubits can represent huge amounts of information; there are exponentially more binary numbers that can co-exist at the same time in the quantum processor than in a classical computer. Even in the face of Moore's Law (the doubling in conventional computer power every year or two) the complexity of massively entangled quantum states of just a few hundred qubits can easily eclipse the capacity of classical information processing. Large scale quantum computers have the potential to operate millions of times faster than today's most advanced supercomputers [1].

Countries that harness the power of quantum computing will be able to revolutionize a wide range of industries, including healthcare, communications, financial services, and transportation. An understanding of quantum computing is also critical to maintain national security and commercial and private cybersecurity because a quantum computer could crack traditional encryption methods based on the factorisation of large numbers. This is recognised across the world. "Global leadership in quantum computing brings with it a military and intelligence edge as well as a competitive advantage in what many expect to be a massive industry in the decades to come," wrote the Committee on Science, Space & Technology of the US House of Representatives in a statement on Sep 13, 2018, the day when the House unanimously approved the National Quantum Initiative Act investing \$1.2bn in a programme with one third of the programme being delivered by the National Institute for Standards and Technology (NIST).

At the moment, two technology platforms are the leading candidates for the implementation of a large-scale quantum computer: trapped ions and superconducting qubits, each having its advantages and drawbacks. While the UK National Quantum Technologies Programme has to date prioritised the ion trap platform, other countries (US, majority of European nations, China, Russia, Canada, Japan) have spread their bets investing in both platforms. Most commercial companies (e.g. IBM, Google, Intel, Rigetti, D-Wave, Alibaba) exclusively develop superconducting processors. SQC no longer belongs solely in the domain of fundamental research, but has become an engineering race. Some liken it to the space race of the past.

Recent years have seen quantum computers based on superconducting chips maturing at a pace exceeding even the most daring expert forecasts. Today relatively small-scale, yet not very practical, superconducting quantum computers are available online to everyone. Larger, exponentially more powerful superconducting processors are being tested in laboratories. Because of the military and security implications of quantum computing it would be complacent to expect that unrestricted access would be granted once these large-scale quantum computers become available in the near future. How soon? Quantum supremacy, when a superconducting quantum computer will be able to solve a particular problem faster than even the most advanced conventional supercomputer, is likely to be achieved before 2020, some even predict this for this year!

British scientists have made pivotal contributions to the field of superconductivity. Recently we have also managed to attract many leading SQC researchers from abroad. Over the years our engineers have created the cryogenic, nanofabrication, software and electronic technology base sufficient to pursue the development of SQC. The SQC test and evaluation capability based at NPL is world-leading.

The main conclusion of this paper is that we believe that on the international stage superconducting technology has matured to the level where it would be prudent for the UK to bring its national expertise and facilities together in a coordinated activity. If a decision were taken to fund a focussed, managed program based on producing an engineered system, we believe this would be able to deliver superconducting quantum computing capability to the UK at the highest aspirational level.

Note added prior to publication:

In draft form we have circulated this document to support the government's recent considerations of the approach to take towards quantum computing and it has been used directly to support the case for investment. As we publish, the Chancellor has announced in the October 2018 budget that "the government will invest a further £235 million to support the development and commercialisation of quantum technologies, including ... £35 million to support a new national quantum computing centre." We hope that this report will continue to be useful in taking the best decisions for the UK in this important strategic direction.

1 INTRODUCTION

Superconducting quantum technology is one of the frontrunners in the race to create commercially viable quantum processors able to solve real-world problems. The long term goal is to build a general-purpose quantum computer with a very large ($\sim$ millions) number of qubits. However, a quantum processor with only ~ 100 logical qubits would already be able to handle problems that would be completely intractable on a classical processor. This number of qubits is now within reach for the leaders in the field.

The present state-of-the-art (at the beginning of the “quantum era”) are processors with a small (3-20) number of qubits able to solve problems such as calculating the spectra of small molecules, e.g. H_2 and LiH , or the binding energy of small nuclei such as deuterium. Larger (up to 72 qubits) processors are currently being tested, but as of this writing no results have been published. This rapid increase in the number of qubits —four qubits would have been state-of-the-art only a few years ago— has been made possible by the inherent scalability of superconducting technology at this level enabled by the fabrication techniques employed. Although there are unresolved engineering challenges, scaling to many hundreds of qubits should be possible using existing technology. Superconducting quantum processors are fabricated using the same techniques and equipment that are used for e.g. CMOS circuits and so can be made in large numbers in a small area. Another advantage is that the qubits are controlled using conventional RF techniques, making controlling large numbers of qubits feasible.

In addition to the general purpose quantum processor introduced above there is another approach known as quantum annealing. The D-Wave 2000Q processor has 2048 qubits but this complexity comes at the cost of having to use very noisy (short lived) qubits. Hence, it is not possible to directly compare the D-Wave processor (or quantum annealers in general) to the type of more general quantum processors pursued by most of the community. Moreover, it is not clear how many qubits would be needed for a quantum annealer to be able to outperform a classical processor. There are now efforts underway to build quantum annealers using long-lived qubits in a major project supported by the US government, including funded work in the UK. Preliminary results on the hardware elements of this coherent annealer have recently been published [2]. A new program on quantum annealing is also underway in Japan.

It is expected that the next generation of generic quantum processors will be based on so-called Noisy Intermediate-Scale Quantum Technology (NISQ). Whereas a general-purpose quantum computer requires a very large number of qubits in order to implement error correction (using a large number of “noisy” physical qubits to implement a smaller number of near-ideal logical qubits), NISQ processors will be able to solve important real-world problems in e.g. chemistry, materials science, finance and logistics using a relatively small number ($\sim 100 - 200$) of qubits. The compromise made is that NISQ processors use no (or very limited) error correction and employ quantum hardware only for those parts of the problem where it is best suited and can outperform conventional classical technology. The best known approaches are so-called variation quantum eigensolvers (VQE) which have already been demonstrated by for example IBM and quantum approximate optimization algorithms (QAOA) pursued by Rigetti Computing.

One key technological difference between future (general-purpose QC) and NISQ processors is that the necessary technology for the latter is mainly a direct extrapolation of our current understanding; that is the technology that needs to be developed should, as far as we know, not require any new fundamental “breakthroughs” but rather builds directly on current state-of-the-art technology. There are now several organisations offering cloud-based access to small-scale quantum processors (e.g. IBM, Rigetti Computing, Alibaba), quantum annealers (D-Wave systems) and advanced software capable of simulating small-scale ($\sim 20 - 40$ qubits) quantum computers (Microsoft). It can be assumed that the cloud-based business model will dominate as we move into the NISQ era and the hardware becomes able to solve commercially interesting problems. The cloud computing model also means that the infrastructure needed to for example cool the quantum processor to millikelvin temperatures becomes invisible to the end user.

Pilot studies being carried out using the current generation of hardware largely reflect what is believed will be the main applications of NISQ processors: quantum chemistry/materials science, finance, logistics, and machine learning/AI. Presently, efforts are focused on understanding exactly which problems in each of these areas would benefit from a real-world advantage by being run on a NISQ processor. This challenge is identified in the 2016 GO-Science Blackett review on quantum technologies [3].

Any project aiming to develop a practical NISQ device will have to balance technological risk, allocated resources and usefulness in the real-world. In this document our working assumption is that a NISQ processor of modest complexity ($\sim 150 - 200$ qubits) that is able to solve a range of important problems in for example quantum chemistry would be a realistic and viable goal for a project that aims to produce a device with significant commercial and societal impact.

This document is divided into three parts. The starting point is a description and set of specifications for a NISQ processor specifically designed for solving certain problems in quantum chemistry. We will then highlight some of the technological problems that would need to be solved in order to actually build this NISQ processor. Finally, we will discuss the resources that would be needed to build such a processor in the UK.

2 THE QUANTUM PROCESSOR

It is likely that the most viable approach for building a *useful* quantum processor in the near future is to create a device tailor-made to run a so-called variational quantum eigensolver (VQE) algorithm. The VQE algorithms have already been used by e.g. IBM, Google, and Rigetti Computing to solve quantum chemistry problems. This algorithm essentially divides the problem of calculating the ground state of, for example, a molecule, into two parts. One part of the algorithm calculates the trial wavefunction – something that would be very costly on a classical computer – and runs on the quantum processor; the output of this is then fed into the second part of the algorithm which runs on a classical processor and is used to find a more optimal solution. By iterating this process many times it is possible to find the (global) optimal solution. The main benefit of this approach is that the combination of classical and quantum processors allows us to solve certain large problems that would be completely intractable on even a supercomputer using relatively few “noisy” qubits. The idea of using a quantum processor in this way is very reminiscent of the way GPUs are already widely used to off-load some calculations from CPUs of classical computers.

The VQE algorithm has already been used to simulate simple molecules such as H_2 and BeH_2 and should be suitable for a wide variety of relatively small but important molecules: examples include the caffeine molecule and other methylxanthine molecules. Perhaps the most widely cited examples are iron-sulphur clusters (see centre of fig. 1) which are important in a range of biochemical reactions; most notably in the respiratory system and therefore of significant interest to the biomedical industry.

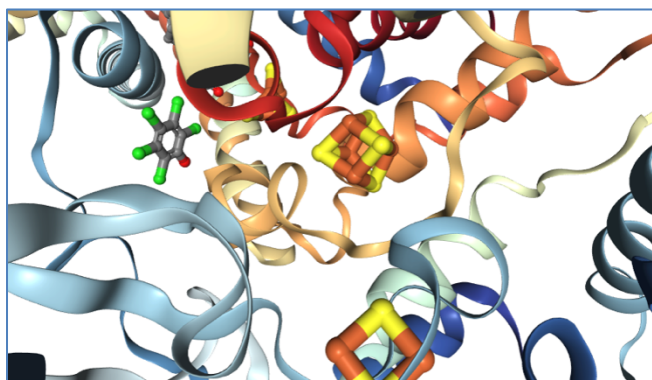


Figure 1. Iron sulphur cluster in mitochondria. An example of a biochemical system that could be studied using a NISQ processor.

One, sometimes overlooked, issue with the VQE algorithm, and indeed with all numerical methods used in quantum chemistry, is that there are strict boundaries when it comes to the accuracy of the calculation. The reason is that we are generally not interested in static situations but rather in the *rate* at which a reaction occurs. These rates are generally determined by very small differences in energy between states [2]. This has led to the concept of “chemical accuracy” equal to 1.6×10^{-3} hartree (the ground state energy of H_2 being 1.0 hartree). Hence, in order for a quantum processor to be useful in the real world it needs to be able to solve for the energies of a molecule with an accuracy better than the chemical accuracy. With existing processors (5-20 qubits) we can of course simply check the answer using a conventional computer, but this will become impossible with more complicated molecules. Hence, developing better methods for benchmarking and uncertainty estimation for large problem running on real-world quantum processors will become increasingly important.

Keeping the above in mind we can now attempt to write down the specifications for a NISQ processor able to execute a VQE algorithm that can solve for the energies of a molecule such as an iron-sulphur cluster. Some of the properties that such a processor would need to have are quite well understood (e.g. the approximate number of qubits needed) whereas others are effectively a best-guess; in the latter case we’ve attempted to give a realistic upper bound.

Whereas the focus here is on quantum simulation using the VQE algorithm it is expected that a quantum processor with these specifications (the same number of qubits, same connectivity etc.) would also be able to solve important optimization problems in e.g. logistics, but the theory for this is less well developed meaning the capabilities are harder to estimate. Another application area that has attracted a lot of attention is finance; e.g. portfolio optimization.

Before proceeding it is worth briefly considering what a complete real-world system with the abovementioned specifications would look like.

The heart of the system (see fig. 2) would be a microfabricated chip with superconducting qubits, control leads etc. The packaged chip would be mounted at the 10 mK stage of a dilution refrigerator equipped with a large (~ 250) number of microwave lines as well as suitable amplifiers etc. Next to the refrigerator there would be a number of racks with interface electronics: microwave generators, arbitrary wave form generator, digitisers etc.; most of which would be controlled using high-speed FPGA-based control modules. Finally, there would be a fast digital computer responsible for executing the classical part of the VQE algorithm. Additionally, there would also be a separate system controller responsible for monitoring and maintaining the qubits at the right operating points. The basic specifications for this systems can be found in figure 3.

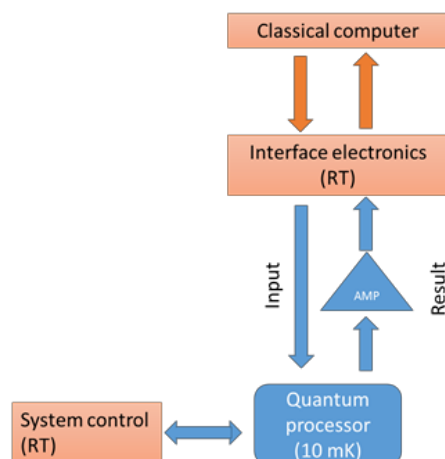


Figure 2. Simplified schematic of a complete system.

Hence, whereas there is no doubt that this would be a large system, mainly due to the amount of microwave electronics needed, we are still firmly in the realm of something the size of a conventional supercomputer.

SPECIFICATIONS FOR NISQ PROCESSOR

- Hybrid quantum-classical system for solving optimization problems
- Variational Quantum Eigensolver (VQE) approach using e.g. Jordan-Wigner mapping
- No direct error correcting scheme (except zero-noise extrapolation)
- ~ 175 qubits
- Vertical integration either using a separate signal layer or using e.g. coaxial qubits
- Error rates: Single qubit gate $\sim 10^{-4}$, two-qubit gate 10^{-3}
- Operated in a commercial dilution refrigerator without e.g. cold multiplexing electronics
- Short-depth circuit connectivity
- Single qubit coherence times 100-250 μs

Figure 3. Specifications for a quantum processor capable of solving real-world problems in quantum chemistry

QUANTUM SIMULATORS

The idea of a quantum simulator was introduced by Richard Feynman in a lecture titled *Simulating Physics with Computers* in 1981. Feynman's key insight was that even moderately complex quantum systems are impossible to simulate on classical computers. The problem is that the amount of information we need to keep track of grows exponentially ($\propto 2^k$). Hence, whereas simulating a system with say two atoms ($k=2$) is easy, the amount of resources needed grows very quickly and a system with only 50 atoms ($\propto 2^{50}$) will always be impossible to simulate on a classical computer.

Feynman's solution was simple: the best way to simulate a quantum system is to use another —controllable— quantum system.

Figure 4. Quantum Simulators

3 CHALLENGES

It follows from the description above that the problems that would need to be solved in order to build such a system fall into three categories. Firstly, the actual quantum hardware needs to be developed and several, as yet unresolved, issues need to be either solved or sufficiently mitigated (coherence times, vertical integration etc.). Secondly, efficiently controlling a large number of qubits using many, potentially hundreds, of high-frequency signals is a significant engineering challenge. Last but not least there is the problem of integrating all the necessary components into a working system.

Here we will highlight five specific challenges:

- Coherence times of individual qubits need to be increased. How many gates (implemented using control pulses) that would be needed for a 175 qubit NISQ QC to execute an optimization algorithm is currently not fully understood. The maximum number of operations scales as the qubit coherence times divided by the time needed for one or two-qubit gate. This means that schemes that use fast gates are preferable but these also pose additional challenges in terms of RF cross-talk. It is widely believed that the key to further extending the coherence times of SC qubits is a better understanding of the underlying materials/surface science of the materials used in their fabrication.
- Reproducibility in the fabrication process is still a major issue. This can to some extent be circumvented by making some parameters, such as the qubit frequency, tunable but at the cost of needing more control signals. Insufficient control over the qubit parameters can also lead to “spectral crowding” making it difficult to frequency-multiplex many qubits.
- Fabrication for vertical integration. Addressing and controlling a large number of qubits requires methods for making connections not only from the edges of a chip but also from above or below. This is standard technology for CMOS electronics but a custom solution that can be used to large-scale superconducting qubit circuits is yet to be fully developed.
- Development of reliable algorithms and schemes for controlling ~100-200 qubits. Whereas existing cryogenic systems can, in theory, cope with the thermal load from all the coaxial cables needed to control close to 400 qubits [3] there are mechanical and practical issues that need to be solved in order to allow for reliable operation. Many of these challenges are akin to what one would encounter in e.g. the development of satellites, meaning this is yet another area where access to specialist skills could potentially speed up development.

- Large scale FPGA/control electronics. Each qubit requires a number of control lines, high-speed (digital) drive electronics as well as associated microwave instrumentation. Solutions for integrating these functions into more compact packages do exist but are typically not available to the academic community because of the associated cost. The skills needed to address this problem are more likely to be found in companies integrating large-scale communication or radar systems.

Only the first two of these challenges involve basic science. This highlights the fact that superconducting quantum technology has now reached a point where specialised engineering skills are becoming increasingly important. Hence, it is likely that most of these challenges could be most efficiently addressed in a coordinated collaboration between the relevant research groups including national laboratories and industry partners with the relevant engineering expertise.

4 RESOURCES NEEDED

The resources that would be needed to successfully carry out this project fall into the same three categories mentioned earlier: quantum hardware, control electronics and integration.

- **Clean room facilities/equipment**
A project of this scope would require access to a state-of-the-art foundry for superconducting circuits as well as facilities equipped with the technology needed to develop the process needed for large scale integration and packaging of circuits. For example, a collaboration between the new SuperFab cleanroom at RHUL and the James Watt Nanofabrication Centre at U. of Glasgow would have the necessary facilities.
- **Test & validation systems**
The project would require access to a number of cryogenic test systems: the main system, comprising a dilution refrigerator equipped to eventually host the fully developed quantum processor, as well as a number of systems that could be used during the R&D phase to optimize the fabrication process and test individual components.
- **Control and interface electronics**
One of the main engineering challenges in this project would be to design, build and deploy the electronics needed to control a large number of qubits. The leading groups in this areas are already using sophisticated FPGA-based hardware to optimize and run their quantum processors. However, the area is still very much in its infancy and it is highly likely that working with entities that already have the expertise and tools needed to develop high-speed digital and analogue electronics would lead to significant gains.
- **Software**
The software stack for this project would encompass a wide range of subsystems: from defining the gate operations on the quantum processor to implementing control software on conventional computers. Hence, this would require a range of skillsets including both quantum physics (i.e. quantum software) and conventional software engineering.
- **System Integration**
The wide scope of this project means that system integration would be a significant challenge. In addition to developing *practical*, and cost-efficient, solutions for how to control the qubits there would also be a wide variety of electronic instrumentation and software that would need to operate seamlessly together. There are also many system parameters (such as latency) that

would need to be controlled since they would have a significant impact on how well the complete system would operate.

5 ENTERING THE QUANTUM RACE

The UK has long been one of world's leading nations when it comes to research on superconductivity and quantum technology (QT, see table 1). Historically, the focus has been on quantum information processing (QIP) research in the AMO (atomic, molecular, optical) area rather than solid-state technology; but over the past few years there has been a marked increase in the number of researchers working on superconducting QT in the UK. This includes a number of new university groups centred round internationally leading scientists that have moved to the UK over the past 5-10 years. This includes well-known pioneers in the field such as Oleg Astafiev (now at Royal Holloway, University of London), Yuri Pashkin (Lancaster University), and Alexander Zagoskin (Loughborough University); a longer list can be found at the end of this report.

Operating qubits in cryogenic environment

Early experiments on superconducting qubits were carried out using “wet” dilution refrigerators. These required expensive liquid helium to operate, but more critically the cooling power was low, not more than about 50 μW . This meant that superconducting qubit experiments were limited to only a few RF control lines.

Today a typical commercial dilution refrigerator is “dry” (requires no liquid helium), push-button, continuously operated system providing a cooling power of 1000 μW and can be bought with 200 factory installed RF lines. Such a system should be able to cool a quantum processor with about 400 qubits. That is, the NISQ processor outlined here could be operated in a system anyone can buy today.

There is no technical reason for why one could not build even bigger dilution refrigerators and this is very likely to happen. This should make it possible to scale up to circuits with perhaps thousands of qubits. However, in order to go beyond this other solutions will need to be found.

One approach currently being developed by several research groups in e.g. Germany and the Netherlands is to use conventional electronics at the 4 K stage of the dilution refrigerator to handle some signal processing tasks. FPGA's operated at 4 K have already been demonstrated and integrated circuits specifically for qubit control are under development. Specialist cryogenic electronics originally developed for e.g. satellites could also be adapted for quantum computing.

Another method also under development is to use superconducting logic (SFQ) to control the qubits. RSFQ is a very well developed Josephson junction technology which works at ~ 10 mK and could therefore be placed near the qubits. This approach has already been demonstrated and is pursued by SeeQC in the UK among others. It should allow for control of tens of thousands of physical qubits with just DC lines.

Finally, optical signals can be sent down the fridge using fibres and converted into microwave pulsed already at the cryogenic stage. This approach was pioneered at NPL to control large addressable Josephson voltage arrays to generate traceable waveforms.

In addition to increasing research strength, the UK is currently seeing the emergence of a nascent industry which is developing quantum software for existing superconducting QC (such the D-Wave or IBM computers) as well as new companies focusing on hardware. Examples include Cambridge Quantum Computing, River Lane Research, Oxford Quantum Circuits and SeeQC UK.

Until very recently the experimental effort on superconducting quantum computing in the UK was quite limited; although researchers at e.g. RHUL, Lancaster and NPL have over the past few years used SC qubits to research microwave quantum optics. The notable exception to this has been the Leek group in Oxford which has, very successfully, focused on research aimed at practical quantum computing. Part of the reason for the focus on small scale (single qubit) circuits has been the lack of state-of-the-art fabrication facilities dedicated to superconducting circuits. However, recent investments in new facilities at RHUL (SuperFab) as well as new equipment installed in existing cleanrooms in e.g. Glasgow and Lancaster have largely solved this issue.

The future of superconducting technology in the UK will depend on a number of factors. The level of funding will, as always, be an important factor, but so is our level of ambition in terms of competing with other nations such as the USA and China (as well as a number of other nations that have declared their interest and created national programs such as Sweden, Japan and Israel) as well as projects within the EU Quantum Flagship program.

Year	What
1926	Paul Dirac presents his pioneering work on a general formulation for quantum mechanics based on non-commuting variables.
1959	Founding of Oxford Instruments, today a world leading manufacturer of nanofabrication and cryogenic equipment that forms the technological basis for solid state quantum computing
1962	Brian Josephson discovers the Josephson effect, the fundamental effect on which all superconducting electronics today relies on (Nobel Prize 1973)
1966	The SLUG (Superconducting low inductance undulating galvanometer) is invented in Cambridge by J. Clarke and can be regarded in many ways as an early robust implementation of a SQUID. This device was essential in demonstrating the universality of the Josephson effect and in accurate determination of the electron charge and Planck's constant.
Early 1980	Terry Clark at Sussex formulates the first ideas about macroscopic quantum tunneling in SQUIDS, an essential phenomena that underpinned the development of superconducting qubits.
1985	David Deutsch, at the University of Oxford, describes the first universal quantum computer.
1995	Andrew Steane (simultaneously with Peter Shor) propose the first schemes for quantum error correction.
1999	D-Wave Systems Inc., the first superconducting quantum computing company founded by Alexandre Zagoskin, now at Loughborough University
1999	First superconducting charge qubit demonstrated at NEC by Yuri Pashkin (now at Lancaster) and coworkers
2003	Anthony J. Leggett is awarded the Nobel prize in physics for his work on macroscopic quantum tunnelling
2009	First Bell-test with entangled superconducting qubits performed by Martin Weides (now in Glasgow) and coworkers.
2010	Quantum optics with superconducting qubits (artificial atoms) demonstrated by Oleg Astafiev (now at RHUL) and co-workers.
2014	The Quantum metrology institute (QMI) is established at NPL to support the emerging quantum industry
2015	The UK cryogenics industry annually underpins £350m gva across industries covering space, particle accelerators, R&D, healthcare and quantum computing.
2015	First fully UK superconducting qubit foundry established (EPSRC investment)
2017	Oxford quantum circuits Ltd, first UK superconducting quantum computing company founded by Peter Leek, Oxford
2018	Oxford university becomes the first academic hub for the IBM Q network

Table 1 Timeline of superconducting quantum technology in the UK. The list also includes leading researchers who are now working in the UK

Here we consider different levels of ambition for SQC in the UK which we denote as levels 0-2:

Level 0. Business as usual.

The UK hosts a number of academically successful groups that will continue to thrive. Some of these groups, as well as various SMEs, will contribute to the worldwide development of this technology and possibly also develop and license some relevant IP.

Level 1. A coordinated effort.

At this level there is a coordinated effort to make the UK internationally competitive in this sector. Commercially, it could mean enabling the development of relevant IP in academic/government funded groups and also supporting SMEs which might be able to develop and sell subsystems for quantum computing to larger commercial entities in e.g. the USA.

A level 1 effort would require increased funding to go into superconducting QT research groups as part of a Phase 2 of the national quantum technologies programme, but also would require finding solutions to a number of structural issues such as:

- **Lack of coordinated funding with a clear focus**
A number of very successful superconducting QT research groups are already operating in the UK but there is currently no funding available for coordinated efforts.
- **Lack of coordination between facilities**
There is no or limited coordination between the various existing facilities for fabrication and measurement of superconducting quantum devices in the UK. This will not only hamper research but can also result in unnecessary duplication of equipment. Moreover, it can also mean that some highly specialised equipment is not available anywhere.
- **Engineering support**
As has been pointed out above, it is the case that many, perhaps most, of the problems that need to be solved in order to scale up QT are of a practical engineering nature. This includes problems related to processing / microfabrication which could e.g. be solved by funding a relatively small number of PhD level specialists that would still work in an academic setting (this is the model used in the Swedish initiative). A possibly more complicated issue is that there is currently no natural (domestic) partner for researchers in the UK that provides help designing electronic components or programming FPGAs etc. This support is, at least to some extent, available to groups working in some European countries (e.g. IMEC in Belgium or KIT in Germany). This could partly be addressed by including superconducting quantum computing within scope for government funding into the commercialisation of quantum technologies.

High-level quantum algorithms and software would be of particular importance in this scenario since they can be tested on simulators or via cloud access to superconducting quantum computers abroad. The software operating at the gate level (e.g. optimal control, pulse shaping and error correction) is hardware specific and would rely on collaboration with foreign hardware developers.

This level of ambition would firmly position the UK as one of the main actors in this emerging field and would enable academic research groups to contribute towards solving some of the issues related to scaling-up outlined earlier. The key enablers for this level would be better coordination between existing groups, and support for the hiring of a small number of specialists that would support and further develop processing capabilities for superconducting QT in existing cleanrooms.

Level 2. Entering the international quantum computing race at scale.

This would entail a national effort to establish the capability to design, develop and build a practical quantum processor of the type that was outlined previously; making the UK world leading in this sector.

The question whether the UK should even try to compete with the USA in this field is of course a contentious one. There is no doubt that companies and academic groups in the USA are the leaders in this area. However, it is also true that this was mainly “blue sky” curiosity driven research until very recently. Over the past 12-18 months we have seen a dramatic ramp up of the efforts focused in actually building practical systems (this can e.g. be seen by looking at the number of engineering positions now opening up at companies working in this area). Moreover, the UK has arguably more expertise in this area than e.g. China, Canada and Russia which has not stopped these countries from investing heavily in superconducting quantum computing. It could also be argued that, the UK not having a significant presence in this field, entails risk; the commercial ramifications of access to practical large-scale quantum computers would be enormous and would impact most sectors of the UK economy. Access to and ownership of key IP is therefore very likely to become vitally important. Hence, a project structured in a way that focuses on problem solving rather than curiosity driven research would be able to make rapid progress.

There are many possible roadmaps to achieve this goal. However, referring to the previously outlined challenges and resources needed, it follows that this is a project which would require strong coordination in order to successfully integrate the many parts needed for a working system. Many of the problems that would need to be solved are, as has been highlighted above, of an engineering nature and probably outside the scope of what can be done solely within a university research group. In order to make rapid progress the project would need an influx of skills not typically associated with quantum technology such electrical engineers, process engineers, software engineers, microwave- and signal integrity engineers etc.

The project would also require the coordination of several parallel lines of R&D in order to rapidly establish some of the necessary supporting technologies, such as quantum-limited parametric read-out amplifiers, that are currently not available in the UK. However, the knowledge needed is in the public domain and well understood meaning there is little doubt that this could be done in a short period of time (~12 months) assuming the facilities (e.g. the SuperFab cleanroom) and manpower was made available.

It follows from the list above and the previous discussion that this project should ideally involve at least one large industrial company specialising in technology integration. The rationale is that in such companies engineering expertise and experience with acting as the integrator for large, technically complex, projects is available. In the UK this would suggest a company from the aerospace or defence sector. Another option would be a consortium of SMEs, research institutes and academia. Regardless of the structure it would face significant project management challenges.

The UK is currently lagging behind the US when it comes to complex multi-qubit circuits. However, we do have a number of excellent capabilities distributed across the country which could be the seedcorn from which to grow a competitive national effort. In our conservative opinion this would take approximately 4 years. Significant outputs at the subsystem level (cryogenics, electronics etc.) and contributions to adjacent applications (e.g., quantum-enhanced sensors) could be expected during this phase. An intermediate scale (a few hundred qubit) quantum processor, NISQ, outlined in this document would then take an additional two years to build and test. This would give the UK its own independent quantum computing capability. However, the rapid progress we are currently seeing in this area means that more ambitious targets could be set once the project is underway.

Level	Ambition	Output	Cost
0	Business as usual	• Excellent research in individual groups • Presence of a few SMEs	Continued funding via EPSRC, Innovate UK, NMS
1	A coordinated effort	• Development of new licensable IP • Development of subsystems that could e.g. be sold to US companies	£30M
2	Entering the quantum race	All-out effort to build a quantum processor led by a systems integrator	£100M

Table 2. Different levels of ambition, output and estimated cost

6 CONCLUSION

In conclusion we recommend that the field of superconducting quantum computing plays a larger part in the future phase of the national quantum technologies programme. A coordinated programme should include academia, national laboratories and industry. Industry is critical to bring engineering skills and a degree of matched co-investment.

Beyond this, the scale of the UK's ambition and the associated scale of future investment in the field should be considered carefully across government and decisions taken quickly. If there is an appetite to invest at scale in the development and construction of the NISQ quantum processor system described above, then we recommend that the programme is configured as an engineering challenge supported by scientific teams. One method of structuring the programme in this way is to have the lead organisation be a major engineering company experienced in design, build and system integration.

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8 UK RESEARCH GROUPS WORKING ON SUPERCONDUCTING QUANTUM COMPUTING

This is a partial list of research groups in the UK focused on research related to superconducting quantum computing. Note, however, that there are many more research groups where there are activities partly related to this field; this is particularly true for theory groups working on quantum information processing since this area is frequently agnostic when it comes to the hardware implementation. Nor does the list include quantum software groups and companies that are already actively using cloud access to quantum processors from IBM, D-Wave and Rigetti Computing.

In alphabetical order:

Oleg Astafiev

Royal Holloway, University of London

Eran Ginossar

University of Surrey

Michael Hartmann

Heriot-Watt University

Peter Leek

University of Oxford

Phil Meeson

SuperFab at Royal Holloway, University of London

Tobias Lindstrom

National Physical Laboratory

Yuri Pashkin

Lancaster University

Paul Warburton

University College London

Martin Weides

University of Glasgow

Alexander Zagorskin

Loughborough University

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