Quantum Computing and Simulations Workshop

5 March 2018

St Hughes College, Oxford

Report on Outputs

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1. Motivation

Today the UK is leading a global race to industrialise this new technology, thanks to the National Quantum Technology Programme, an alliance of academia, industry and government brought together to exploit our research strengths. But international competitors are catching up fast. To stay in front and reap the rewards, we need to maintain the momentum that has been established in phase one of the programme.

Over the next 5 to 10 years, commercial quantum technology devices are likely to become as prolific and profitable as today's electronics. They will have a huge impact on our lives, benefitting healthcare, defence, security, aerospace, transport, civil engineering, telecoms and finance. Many advances that we expect to shape our future industrial strategy depend on technology that is not available today, but can be delivered by second generation quantum technologies.

EPSRC is planning for future investment in the area of quantum technologies and this involves identifying quantum technology research challenges and priorities for the UK. This workshop was focussed on the research challenges and priorities in the area of Quantum Computing and simulation.

2. Objectives

The objective of the workshop was to bring together technical experts from industry and academia working in the UK in areas of direct relevance to Quantum Computing and Simulation to identify and discuss research challenges and priorities for the UK in Quantum computing and simulation for the next phase of funding (2019-2024) and beyond. The event was also to discuss and identify expertise skills that will be needed and any international collaborations that would be appropriate.

3. Background

The existing EPSRC Quantum Technology Hubs end in November 2019. There is agreement amongst the delivery partners and strategic advisors of the UK National Quantum Technologies Programme that a second phase of the National Programme should include a substantial technological research programme delivered through Hubs. This approach is supported by the Quantum Technologies: Blackett Review "The Quantum age: technological opportunities".

It is envisaged that the Quantum Technologies research programme will be a smaller proportion of a second phase of the National Programme than is the case in the first phase of the National Programme, and will be joined by new instruments such as Innovation Centres and Challenge Programmes.

Research conducted in the second phase should be integrated with the wider research and innovation landscape and investments. There is ongoing uncertainty over the financial envelope in a second phase period. The existing Quantum Technology Hubs have established capabilities and expertise which should be built upon.

3.1 Future research priorities and Hub portfolio

There are three stages to identifying future research priorities and refreshing the Quantum Technologies Hubs portfolio

(A) Research priorities in quantum technologies and for research Hubs (January to March 2018).

Engagement with Quantum Technology Hubs, quantum technology researchers, non-quantum technology researchers, industry and users, to obtain perspectives on the research challenges and opportunities in quantum technology, and development of these into research priorities for a second period of the National Programme.

This workshop forms part of the activities under this early stage of the process:

a. Identifying technological research priorities
b. Providing information that can be used in scoping the research programme in a second phase of the National Quantum Technologies Programme, in terms of priorities, disciplines and perspectives that should be involved
c. Quantum Technology research hubs are envisaged as being part of an overall landscape of research and innovation in a second phase, and will need to work with other activities
d. It is only part of the process, and attending this workshop does not guarantee participation in Hub consortia, and non-attendance doesn't exclude it
e. EPSRC are working closely with our National Programme delivery partners, in particular Innovate UK in this process

(B) Identifying Hub partners (April to October 2018)

Identification of the research priorities that should be addressed by Quantum Technology Research Hubs in a second phase, development of a vision for a Hub portfolio, and the formation of consortia to deliver this Hub portfolio.

(C) Developing Hub proposals (November 2018 to March 2019)

Development of proposals Quantum Technology Research Hubs which will address the most important research priorities in quantum technologies for the UK in a second phase period of the National Programme. Including their assessment and preparation for making awards.

4. Delegate Selection

Delegates were selected based on their expertise in quantum computing and simulation and associated areas of research. This included representatives from major investments made through the National Programme, including the Quantum Technology Hubs, Quantum Technology Fellows, Quantum Technology Capital grant holders, as well as holders of other EPSRC grants.

Participants were selected based on advice from the National Programme Strategic Advisory Board (SAB), members of EPSRC's Strategic Advisory Network and Strategic Advisory Teams, and the Quantum Technology Hubs. This was to ensure a balanced group, with a diverse representation of technical expertise and a diverse representation of institutions and industry from across the quantum communications and simulation domain. Attendees are shown in Annex 1.

5. Agenda for the Quantum Computing and Simulation Workshop

09:30 – 10:00	**Registration and coffee**
10:00 – 10:15	**Aim of the workshop** Presenter: Dr Liam Blackwell
10:15 – 10:30	**“Platforms for Quantum Information Processing: the UK choices compared with World Wide Activity for Simulation and Computation “** Presenter: Professor Sir Peter Knight
10:30 – 10:50	**“Critical issues for scalability”** Presenter: Professor Simon Benjamin
10:50 – 11:10	**Q & A following presentations**
11:10 – 12.15	**Breakout session 1** Research challenges in Quantum Computing and Simulation in the UK
12:15 – 12:45	**Breakout session 2** Grouping session 1 Research challenges
12:45 – 13:25	**Lunch**
13:25 – 14:00	**Discussion topic following the morning session** What are the key challenges the UK should tackle and what expertise needs to be involved?
14:00 – 14:15	**The need for UK research priorities** Presenter: Dr Liam Blackwell
14:15 – 14:45	**Predicted phase one progress of NQIT** Presenter: Professor Ian Walmsley
14:45 – 15:15	**Q & A** (followed by coffee break)
15:15 – 16:00	**Breakout session 3** Identifying key streams of research for the second phase in the UK
16:00 – 16:15	**What Happens next?**
16.15	**Workshop closes**

6. Workshop Outputs

During the workshop, participants had the opportunity to contribute input via a number of facilitated sessions, together with hearing from three speakers on “Platforms for Quantum Information Processing: the UK choices compared with World Wide Activity for Simulation and Computation”; “Critical issues for scalability” and the “Predicted phase one progress of NQIT”.

In the first facilitation session (breakout session 1) groups discussed and then captured research challenges in quantum computing and simulation for the UK over two time frames 2019 – 2024 and beyond 2024. The groups completed proforma’s identifying both hardware and software research challenges. Following this session, the same groups considered the research challenges they had identified and in breakout session 2 they grouped their research challenges in three ways:

- Challenges that hinder scalability
- Challenges that do not hinder or are not relevant to scalability
- Challenges that are not device dependent

The proforma from session one with the groupings (reflected by colour coding) from session two can be found at annex 2: workshop proformas.

There were two facilitated sessions in the afternoon. The first of these was a discussion on the key challenges the UK should tackle and what expertise needs to be involved. Each table considered a different aspect of this.

The final facilitated session of the day was breakout session three. For this session, participants were each asked to capture on post it notes the three key research challenges that they feel the UK should prioritise in the second phase. Once they had done this, in their table groupings, these were discussed and clustered. The groups were asked to consider when clustering what is the best way to deliver the research priorities, for example what should be the priorities of a research hub in this area; what would be well suited to fellowships; training and skills or other funding routes.

At the end of the day, participants were given the opportunity to capture anything else they wanted to add.

The typed up outputs for each facilitated session are included in Annex 2.

7. Summary

Some initial observations from the outputs are:

- The majority of the hardware challenges captured in session one were grouped as research challenges that hinder scalability in session two.
- There are a large number of hardware and software challenges that are not device dependent. However, it was noted that although the challenges may not be dependent on specific hardware and could be challenges that apply broadly, their solution may be hardware specific.

The workshop raised a number of questions regarding priorities for the UK in quantum computing and simulation, which relate to the hardware platforms which should be developed, whether to pursue co-processors and universal quantum computers, and the most appropriate approach to the intergration of research in hardware and software. This workshop provides some useful information which can be used to reach answers to these questions, and this will help the identification of priorities in the quantum computing and simulation area as a whole. The need for a Research Hub in this area was reinforced alongside the highlighting of opportunities for other approaches in research and innovation in quantum computing and simulation.

8. Next Steps

This report will be emailed to attendees and added to the EPSRC website. The report will be considered as a key input in discussions with our delivery partners on the National Quantum Technologies Programme and its Strategic Advisory Board on priorities for Quantum Technologies Research Hubs in a second phase.

EPSRC have run workshops in other quantum technology areas and there will be workshop reports produced for each of the workshops. In addition to the workshops, EPSRC are gathering input from a range of sources which will also feed into discussions on research and innovation priorities. The scope for Quantum Technologies Research Hubs in a second phase of the National Programme will be published in June, with details of how to register an interest in being part of a Hub's consortia.

The input received from the workshops and other engagement will also be used by the EPSRC Quantum Technologies Theme when planning future activities and funding.

Annex 1: Workshop Attendees

Name	**Organisation**
Almut Beige	University of Leeds
Amanda Howes	EPSRC
Andrew Daley	University of Strathclyde
Arzhang Ardavan	University of Oxford
David Lucas	University of Oxford
Dominic O'Brien	University of Oxford
Earl Campbell	University of Sheffield
Evert Guertsen	University of Oxford
Helen Hunt	EPSRC
Ian Walmsley	University of Oxford
Jason Smith	University of Oxford
John Morton	University College London
Liam Blackwell	EPSRC
Mark Everitt	Loughborough University
Myungshik Kim	Imperial College London
Noah Linden	University of Bristol
Paul Warburton	University College London
Peter Campbell	NCSC
Peter Knight	NPL
Petros Wallden	University of Edinburgh
Phil Meeson	Royal Holloway University London
Raffaele Santagati	University of Bristol
Richard Curry	University of Manchester
Roberto Desimone	BAE Systems
Simon Benjamin	University of Oxford
Simone Severini	University College London
Steve Brierley	University of Cambridge
Tobias Lindstrom	NPL
Viv Kendon	Durham University
Wendy Carr	EPSRC
Winfried Hensinger	University of Sussex

Annex 2: Workshop proforma

BREAKOUT SESSION ONE AND SESSION TWO OUTPUTS

The proformas below are those completed during session one of the workshop. Each table completed a proforma on hardware research challenges and software research challenges as discussed by the group.

During session two, using their completed proformas from session one, the tables grouped the research challenges captured in the following ways:

- Red = Research challenges that hinder scalability
- Blue = Research challenges that do not hinder or are not relevant to scalability
- Yellow = Research challenges that are not device dependent

The grouping is indicated with a word / colour next to each research challenge in the proformas below:

Proformas and grouping of table one

This table's definition of yellow is "The Answer to the challenge may be device dependent. The question raised by the challenge applies broadly"

The definitions for blue and red are unchanged.

Table one - What are the HARDWARE research challenges in the area for the UK ALL HARDWARE CHALLENGES LISTED BELOW ARE RED

In the medium term 2019 – 2024 Non Error Corrected

	INIT.	SINGLE QUBIT FID	MULTI-QUBIT FID IN SCALED SYSTEM	NETWORK BEYOND NEAREST-NEIGHBOUR	READ OUT FID.	SCALE TO…	SCALING ROUTE TO… ⟷	QUBIT UNIFOR - MITY
ION TRAPS	Already 99.99% in lab (maintain at scale)	Already 99.9999% in lab (maintain at scale)	Target: 10^{-4} 10^{-3} scalably REPRODUCIBILITY (two groups have verified)	Low loss photonics Improved detectors. High port count switch	Cavities to improve ion -> portal coupling	1000's ↓ ………….. Modular: 20 / module 100's of modules	Integration; Miniaturisation; Synchronisation; Simplification	
SUPERCONDUCTING QUBITS		— — — — — Materials science	99.6% Now -> improve & scale — — — — — — — — — — Cross	Key challenge networking techniques talk	Key issue Bottleneck of 1% error	~ 300		
SILICON SPIN QUBITS	N/A	Today: 10^{-4} Target: 10^{-4} in scaled system. — — — — — — — — .Understanding charge noise technology / .Design of qubit	Today: 10^{-2} Target: 10^{-3} in scaled system. — — — — — — — — — — relation between and fabrication qubit design. gates		• More compact read out using gate reflectometry. • Read out speed. Target <1µs with 99% Fid	~50	~10^4 -> use CMOS / foundry-made qubits / architecture. -> Some cryo-CMOS control	High Yield Foundry Fabri-cation
ALL-PHOTONIC				* Low loss * networks High port count switch * *				

MOLECULES			Electrical spin Hamiltonian control	* See scaling route		Electrical read out	*Key challenge: directed self-assembly of arbitrary functional molecule networks	N/A Built in
NV CENTRES	~ 99% -> Improve a bit Materials science & control Engineering	~ 99% -> Improve	~ 99% -> Improve How?	Photonics	~95%	Increase yield of useful qubits Engineered' chips w/off chip connectorization		Cheap to scale up if solved

Managing Public & Company expectations with:
- Good outreach
- Good RRI
- Widely agreed milestone

~~In the long term (beyond 2024)~~

GENERAL YELLOW
- Verification (see software)
- Full architecture simulation (see software)
- Cross-talk

ENABLING TECHNOLOGIES

- Low-loss optical switches (errors below few %) Ion traps + Photonics? (though, NB wavelength dependent)
YELLOW
- Cryogenic + low power control electronics Silicon + Supercon + NV + Ion traps? YELLOW
- Integrated (+ Cryo) microwave electronics (sources, switches, detectors) Many… YELLOW
- Control hardware + control software (low-level) Many… YELLOW
- Frequency conversion YELLOW
    - Microwave / optical conversion
    - Blue light / telecoms conv.

SYSTEMS ENGINEERING

- Engineering / Quantum End – To – End models YELLOW

Table one - What are the SOFTWARE research challenges in the area for the UK

In the medium term 2019 – 2024

Small scale algorithms. BLUE

Optimisation of, including good compiler software RED

Identify problems useful on 50-100s machine

- Useful = practical application with proven? advantage
- Identify other domains where potential advantage : working with chemistry, materials scientists
- What is possible without error correction. "Error mitigation"
- Interplay between crypto and computation , e.g. privacy

+ New algorithms for noisy devices (error Resilient) YELLOW

Feedback loop between Software and HW RED

Better understanding of classical methods BLUE of simulating quantum computer

What noise levels result in a algorithm being easy to classically simulate YELLOW

Verification schemes for practical use

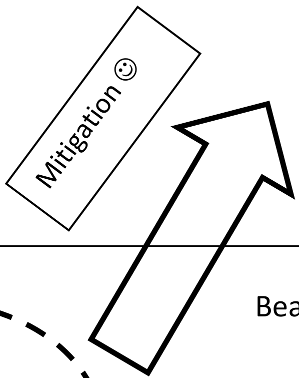
Certification methods like random-benchmarking but on a larger scale .e.g. hypothesis testing YELLOW

Fundamentally new Algorithms BLUE

Dev of software that performing classical simulation BLUE

New architecture taking into Account network requirements YELLOW

Take advantage of noise BLUE



In the long term (beyond 2024)

Beat the Toric code (error correction with a factor of 10) RED

Identify fundamental quantum components of algorithms

Fully secure protocols to use distributed processors BLUE YELLOW

Software – methods for compliation of large circuits, including scheduling Qubit traffic RED

Proforma and grouping of table two

This table's definition of yellow is "Challenge not dependant on specific hardware but solution may be hardware specific

The definitions for Red is unchanged.

The definition for Blue changes at the bottom of the software proforma where clarification is made.

Table two - What are the HARDWARE research challenges in the area for the UK

In the medium term 2019 – 2024

QUBITS

- Ion traps
  Clear from NQIT RED
- Increase fidelity of 2 qubit interactions from 99.91% to 99.99% RED
- Other qubit integration BLUE RED

PHOTONIC NETWORKS RED

- Low loss components at the correct wavelength RED
- Fast switching for photonic quantum devices RED
- Optical interfacing with Q system RED

OTHER TECH

- Neutral atoms + Rydberg physics optical lattices have science strengths for Q simulators. Challenge is control for these systems RED
- Assessment of other hardware candidates which can operate useful simulations better and their connectivity BLUE YELLOW

GOING SMALL

- Vacuum systems RED
- Integration with optics RED
- Fabrication technology RED

LINKED

(tools)

Developing fabrication tech (specific)
for making quantum systems RED

Needs different specification than microelectronics fabrication

Training of engineer in fabrication
For QT platforms RED YELLOW

In the long term (beyond 2024)

Theory and Experiment

- Challenge to generate genuine scalability to >1000 Qubits RED
- Develop useful co-processors (short term: link to software and potential additional hardware platforms) BLUE

Table two: What are the SOFTWARE research challenges in the area for the UK

In the medium term 2019 – 2024

- Better understand software applications for quantum simulators RED
- Have an IBM, Google, Alibaba rival RED YELLOW
- Understanding of (hardware) requirements RED
- Specific early applications in detail and threshold #qubits to be useful RED YELLOW
- Hardware / software co-design RED
- Hardware specific Q software RED
- Risk of losing early career trainees if no UK hardware to use BLUE YELLOW
- Access to UK hardware for testing software RED YELLOW
- Optimisation of hybrid algorithm onto available hardware YELLOW
- Machine learning for improving tolerance to noise of quantum algorithms YELLOW
- Hardware access in same local network = site as HPC for hybrid algorithm development YELLOW
- Build software library of composable q. sim components for range of practical hybrid simulation solution RED YELLOW
  - Fault detection
  - Drug discovery
  - Operations management
  - Vehicle design
- Training of PhD students on a level of hardware + software w/ connections to <u>real</u> industry problems and language BLUE YELLOW
- Master courses to send the quantum message to industry BLUE YELLOW
- Time critical algorithms = need answer fast BLUE
- Quantum system engineering RED YELLOW
  - Understand how to develop hybrid solution additives
  - How to validate hybrid systems

BLUE – THE FOLLOWING ARE ALL BLUE – THEY ARE HINDERED BY THE LACK OF SCALABILITY <u>BUT</u> DOES <u>NOT</u> HINDER SCALABILITY

- Understand size of market opportunities related to hybrid solutions YELLOW
- Build ongoing dialogue with industry YELLOW
- Characterise “range” of practical business applications that benefit from hybrid solution - YELLOW
  - Distribution logistics
  - Operations management
  - Optimised planning and scheduling
- Quantum systems engineer YELLOW

  - Reliability specialists
  - Test and validation
  - Risk management
- Software to compute size of quantum processor for specific business application YELLOW
- Grand challenges (e.g. DARPA)) for specific goals YELLOW
  - Optimise transport networks
  - Simulate protein molecule
  - Fault diagnosis
    - Financial fraud
    - Complex productive analysis
- Understand business metrics for BLUE YELLOW
  - Industry } funding
  - Venture capital

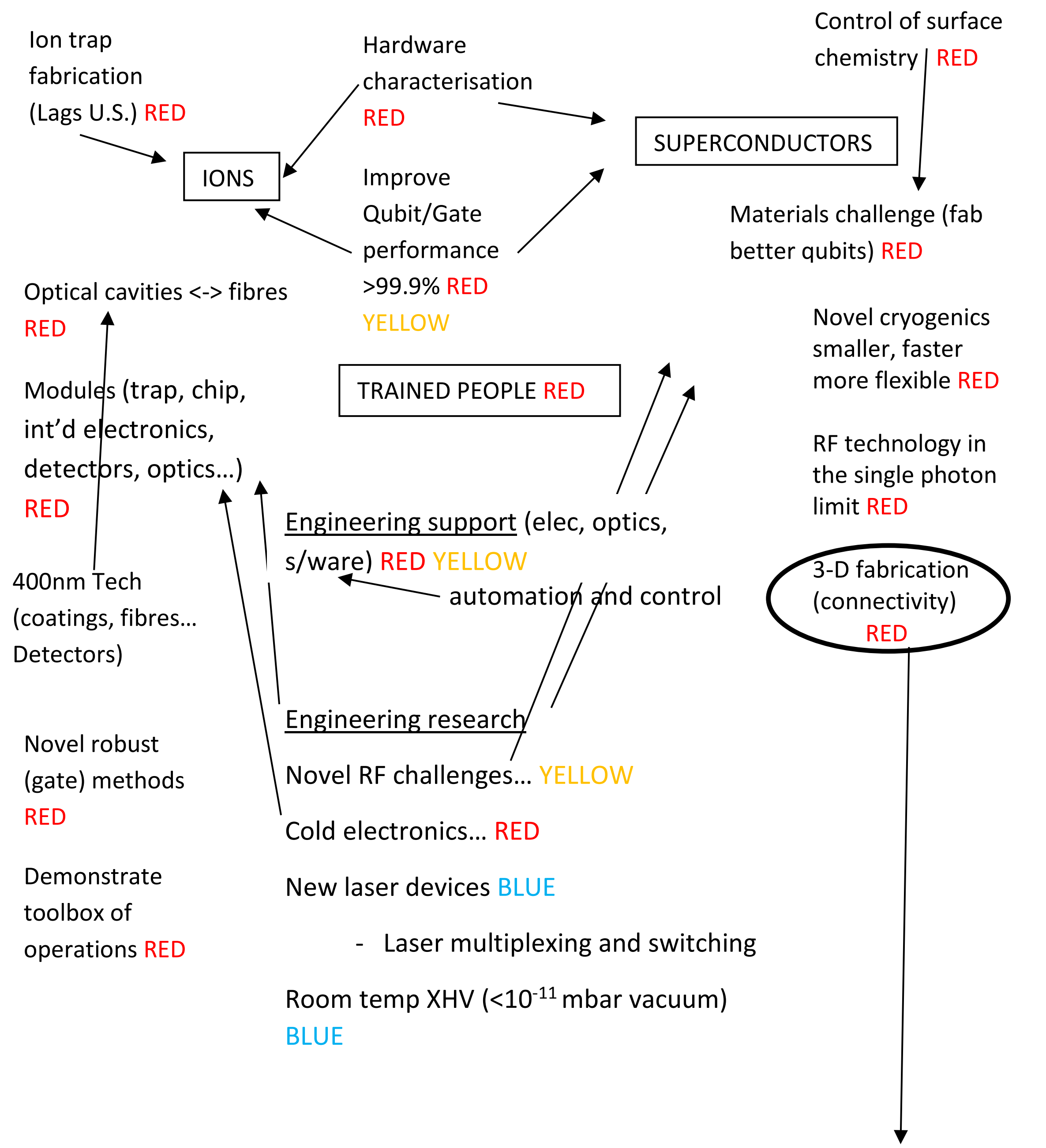
In the long term (beyond 2024)

- Develop a programing toolbox usable by non-specialists (classical problem -> quantum algorithm) YELLOW
- Integrate physics and industry fully in research and training YELLOW
- Use appropriate language + address appropriate problems for industry YELLOW
- Ethical and cultural implications of introducing hybrid solution into mainstream public life YELLOW
- New quantum algorithms (without application!) YELLOW

Proforma and grouping of table three

Table three: What are the HARDWARE research challenges in the area for the UK

In the medium term 2019 – 2024



In the long term (beyond 2024)
All the above plus:
Scaling up (>100 qubits)

- Cheaper devices (?)
- Reliability RED
- Reproducibility RED
- Verification YELLOW

- Multiplexing µW RED
- Cold electronics (+ fast?) RED

Table three: What are the SOFTWARE research challenges in the area for the UK
In the medium term 2019 – 2024 • Trained people • Optimising algorithms for specific hardware, e.g. network specific algorithms • Mapping hard, useful classical algorithms > Q algorithms YELLOW (medium & long term) • Useful algorithms for 10 to 50 qubit machines RED - validation and verification BLUE sub universal QC (medium term) • Study trade off : connectivity / number qubits YELLOW • Focus on use cases YELLOW • Identify low hanging fruit YELLOW • Compare different error correction in the context of different hardware RED
In the long term (beyond 2024)

Proforma and grouping of table four

This table did not group the software challenges

Table four: What are the HARDWARE research challenges in the area for the UK

In the medium term 2019 – 2024

- Qubit connectivity RED
- Qubit fidelity and error correction RED YELLOW
- Engineering scalability RED YELLOW (inc connectorization)YELLOW
  - Optical networked cluster state architecture
    - Entangler
    - overlap to detector

SQEPs

- Density and thermal management RED YELLOW
- Optical networking RED YELLOW
  - Non-commercial lasers
  - Wavelength conversion
  - Switching / modulators in fibre
  - Non-standard wavelength
  - Fibres and fibre coupling
  - Isolators
  - detectors
  - Single photon sources
- Control electronics (FPGA, DDS) RED YELLOW
- Materials and manufacturing RED YELLOW
  - Materials for vac system
  - Optical isolator
  - Waveguide platform
- Components and supply chains RED YELLOW
  - Packaged modules for optics
  - Microwave interfaces
  - Vacuum system developments
- Tools for modelling and simulation for computer aided engineering of hardware (including system integration & design for test).
- Also higher level and hierarchy modelling RED YELLOW
- Systems engineering RED YELLOW
  - Identification of stakeholder needs
  - Modelling and simulation (from supply chains to devices)
  - Linking functions to quantified testable performance requirements
  - Validation and verification criteria
  - Identification of critical parameters
  - Improved productivity (EGT 30%)
  - Documentation
    - Traceability
    - Reproducibility
    - Know-how retention
    - Data recording and retrieval
  - Complexity and sensitivity analysis (What happens if I change component X?)

In the long term (beyond 2024)

- Miniaturisation BLUE YELLOW
- Efficient fault tolerant qubits at scale RED YELLOW
- Manufacture scale up RED YELLOW

Table Four: What are the SOFTWARE research challenges in the area for the UK

In the medium term 2019 – 2024

- Identify problems to solve on small noisy processors
- Quantum modelling of nonlinear optical systems
- Skills ← Device characterisation
  - Programming hardware for small noisy processors
  - Cloud-based algorithms & interfaces
- Application discovery and understanding quantum advantage ← Complete and unambiguous system requirements
- Verification and validation
- Architectures for hybrid quantum / classical processors
- Error mitigation strategies

In the long term (beyond 2024)

- Protein folding
- Drug discovery (Grover?)

OUTPUTS ON DISCUSSION SESSION

The tables were asked to discuss "what are the key challenges the UK should tackle and what expertise needs to be involved?" and capture key points

Each table tackled a different aspect:

Table one: Key challenges to deliver scalable hardware:

Scalable = Arbitrarily Large
Order (10^6 qubits) fault tolerant fidelity

Questions

1. Does it make sense to invest in hardware that does not scale? Perhaps not?
2. Systems that reach the scale of order (1,000 – 10,000) qubits can be useful, but getting there from where we are now requires overcoming some scaling challenges
3. How to balance investment in building intermediate scale quantum hardware versus overcoming challenges for going much larger?

Table two: Key challenges to deliver hardware that doesn't need to scale further

- Why would you work on something that does not scale?
- Co-processor requires small scale system (but still needs scaling i.e. 50 Qubits)
- Does that include modular components?
- Schemes not feasible to scale but useful
- Develop ion traps to make a small network for co-processing

Table three: Key challenges to deliver device specific software

- Hardware for said software not all prioritised so far e.g. UK has science excellence outside of Hubs good for quantum sim (e.g. atoms, / Rydbergs) –> opportunities
- Work closely between theory and expt (same funding for both)
- Identify platforms and problems + get them well matched
  - Algorithms and expt ←----------→ industry and academia
- "quantum control" level of optimisation
- Thinking differently + joining up skills beyond typical physics PhD skills
  - Training implications, bring in engineers and Computer Scientists
- Q env con –> hardware specific hope to get numbers reasonable
- Map problems to different Hamiltonians

Table four: Key challenges to deliver independent software
• Identify applications where quantum algorithms can make a difference. Right mix: complexity analysis – business application specialists (bit like behaviour in ITRS). Broad reach & extended over time. • Establishing size of resource needed • Not enough quantum software engineers • We lack a notional capability map – also what capacity is needed. • Platforms to run algorithms needed and evaluated • Device independent modelling and simulation – such as of idealised devices with tunable parameters (for e.g. identification of stability issues and critical parameters)

BREAKOUT SESSION THREE OUTPUTS

Each table selected priorities and clustered them:

Table one

Clustering (one square is a cluster)

Focus on (arbitrarily) scalable approach to quantum computing Network structure crucial for truly scalable <u>Develop and demo</u> Reconfigurable network of small processors in a resource-efficient way	Directed assembly of molecular components	Validation, verification, certification : from individual experimental parts to full universal quantum computing towards • Standardised requirements -> industry adaption Verification & testing
Improved ion trap performance at scale - EAV (Understanding of fabrication and performance) Making high fidelity qubits using existing foundry grade (e.g. CMOS) technology – -> demonstrates very large scaling potential	Photonic technologies for computing Low loss photonic networks and switches A cheap low-loss optical multiplexer compatible with ion-trap architecture, thus solving the current scalability bottleneck faced by NQIT	Quantum software – broadly interpreted An <u>integrated</u> software STACK project. Bringing together quantum control, error correction, emulation, compiling, everything. Improved error correction and mitigation Develop a full theory of: quantum error <u>mitigation,</u> i.e. learning to minimise errors without using costly Q.E <u>correction</u>
Establish this Feedback to Develop <u>Optimised Manufacturable</u> Quantum processors able to scale to millions of Qubits Quantum architecture design & modelling ↔ Test & measurement (at millikelvin) ↔ Fab/ Foundry ↔ Quantum architecture design & modelling	Develop a suite of enabling "classical" tech inc. control hardware, microwave and DC signal processing, …… low power and operating at cryogenic (<4k) temp.	Quantum chemistry application for few qubit devices, complemented by understanding of best classical methods. E.g. classical cluster versus quantum variational Research in finding useful applications/ algorithms with O (100) noisy qubits - General (device independent) - Tailor-made (for specific device)

Comments on priorities and funding:

- All funded with Hub structure
- Fellowships should be kept <u>open</u> to get best people
- Skills and training used to support all of these

Two models for software discussed:

A – Quantum software hub (separate)
B –Software integrated with QC Hub that covers multiple leading hardware platforms

(All agreed that software needs proper resourcing and broad research community)

<table>
<tr><th colspan="3">Table two</th></tr>
<tr><td colspan="3">Clustering – one square per cluster. Priorities for (a)Hubs, (b)fellowships and (c) training funding routes (letters after priorities indicate possible funding route)</td></tr>
<tr>
<td>PHOTONICS / NETWORKS
Networks & interconnects to leverage photonics strengths - in many wavelengths and frequency connections. a,b

Interconnects & new techniques based on Diamond colour centres and superconductivity < > optical interfaces. a,b

High quality qubit sources. a,b</td>
<td>SCALABLE Q COMP. ION TRAP
Networked ion trap quantum computing (modules and networked) –> scale up. a

Fabrication (for scaling) of components for quantum comp / sim.
electronics, vacuum, sys, photonics. a, b

50 – 100 qubit quantum processor (photons / ions) a</td>
<td rowspan="2">ALGO / SOFT
Algorithm development for hardware prioritised in UK – all aspects from science to solving industry problem. a, b

Interdisciplinary research in quantum simulations for materials. b (and other streams and industry)

New routes to error resilience and correction. a,b (and other)

Software… Architecture software etc. for Q comp / sim a, b

Build software library of generic / composable quantum simulation components for more complex simulation needed.
- Fault detection
- Any discovery
- Reliable design
a, b (and other)

Characterise <u>RANGE</u> of applications amenable to hybrid solutions, e.g. distribution logistics, operations management, financial fraud detection. b (and Innovate)</td>
</tr>
<tr>
<td>TRAINING
Train innovative quantum scientists who are aware of the markets. c

Masters and short courses for industry. b, c

Training of engineers in quantum, not just Q scientists training in engineering. c

Train and have more skilled people working on quantum computers. c</td>
<td>OTHER HARDWARE
Hardware platforms for quantum simulators that can also form co-processors for hybrid algorithms. a, b

Quantum simulation based on neutral atoms as a quantum co-processor. (hardware and theory). a, b

Near term application specific quantum information processing machines. a

Hybrid platforms for quantum technologies, e.g. NV in diamonds or si Vacancies centre with linear optical networks. a, b</td>
</tr>
</table>

		Hybrid quantum computation software. B (and other) Quantum system engineering. - Principles of design - Metrics - Validation and verification a (and industry) Integrations of Software and hardware to build a computing system. a

<table>
<tr><th colspan="3">Table three</th></tr>
<tr><td colspan="3">Clustering – one square per cluster. Priorities for (A) training , (B)Hubs (C) fellowships and (D) Programme grant funding routes (letters after priorities indicate possible funding route)</td></tr>
<tr>
<td rowspan="2">Cryogenics for real world applications

Hardware specific error correction

Quantum error “mitigation” ideas

Fundamental material research underpinning superconducting quantum devices</td>
<td rowspan="4">Automation B,A

Cold electronics C,B

Ion trap modules including ion chips, voltage generating, detectors and FP6A’s B,A

RF and microwave electronics and rf amplification. B,A

Teams for senior people will be needed for most challenges. D

Non-error-corrected quantum computation (e.g. annealing) C.D

Microwave quantum optics C

Quantum metamaterials

Optimising quantum complier for modular hardware

Novel robust gate methods C, B

Industry motivated problems for small / noisy computer</td>
<td>Quantum comp/sim using superconducting qubits. B

Underpinning technologies for superconducting qubits (RF tech and cryogenics)</td>
</tr>
<tr>
<td>Translate algorithms to gate systems B,A,C

Matter qubit <-> Photon interfacing. A,B

Ion trap hardware dev.
E.g.
- Chip fab
- Optical delivery
B,A</td>
</tr>
<tr>
<td>Cryo (classical) control electronics (e.g. RSFQ)</td>
<td rowspan="2">Development of quantum algorithms for small scale devices C,A</td>
</tr>
<tr>
<td>Map interesting problems to quantum algorithms. C,A</td>
</tr>
</table>

	Materials for QC (defects, dielectric noise, etc.)	

<table>
<tr><td colspan="2">Table four</td></tr>
<tr><td colspan="2">Clustering of priorities into Hubs, Fellowships, Training, Innovation Centres, Other. One square per cluster</td></tr>
<tr><td rowspan="3">HUBS
Short term noisy quantum computers : applications for industry – hubs, Innovate

Working demonstrator (2 x 5 qubit min)

Materials and manufacturing research to solve QC open challenges especially optical / superconductor

Systems engineering (including research into appropriate depth and scope)

Quantum network technologies (especially optical)

Linear optics quantum computer

Hybrid quantum computers (ion traps)

Q materials – spin, photonics, low temp superconductors

Q. devices & networks
- addressing, using, combining

Qubit fidelity and connectivity

Materials engineering

Cold atom simulators

Engineering of solid state chips with multiple nodes</td>
<td>FELLOWSHIPS
Quantum skills

• Training centres
• Fellows
• Industry

Theory of quantum algorithms / quantum complexity theory – Fellowships, CDTs</td></tr>
<tr><td>TRAINING
Quantum information : basic science

Fellowships, CDTs, responsive mode

• Skills
o Electronics / software / mechanical / design
o Low level implantation</td></tr>
<tr><td rowspan="2">INNOVATION CENTRES
Control systems
• Optical
• Electronic
• Connectivity

Application discovery

Quantum sensors

Scaling capability and resources (skills, processes, manufacturing, partners)</td></tr>
<tr><td>OTHER

Reliability facility including accelerated failure</td></tr>
</table>

Attendees were than asked to capture anything else they wished to add

There needs to be a stronger emphasis in Phase 2 on Quantum Systems engineering either as a separate Hub or a component of each Hub

Industry needs to convinced that the field is maturing with rigorous areas such as

- Principles of quantum design and architectures
- Metrics for effective quantum hybrid solutions
- Validation and verification