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Quantum Landscape Outlook 2021

[Home](#) / [Quantum Landscape Outlook 2021](#)By [David Shaw](#) | [📅 21st December 2020](#) |

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Nations and regions around the world are continuing the rapid build-out of publicly funded quantum technology initiatives. Everyone wants to build a future quantum ecosystem in their own back yard. In the commercial space, the bounds of international collaboration are beginning to emerge. Investors need to dress for all seasons.

Governments around the world have come to realise that quantum technology is a set of interlinked technological future opportunities that span not just quantum computing, but also quantum communications, timing, sensing and imaging. Importantly there are connections between these ecosystems and across their supply chains.

Governments have responded by launching quantum technology programmes to help develop this important future tech and secure their share of the economic benefits. In 2019 governments scrambled to get to a \$1b programme promise. In 2020 the aspirations and the spending bar have marched inexorably upwards.

Quantum accounting – National spending claims are increasingly hard to vet for comparability. Is a portion of continuing basic scientific research spending included? Is matched funding from industry being assumed? Is this still

R&D or infrastructure rollout? Do national and regional spending totals constitute a double count?

For a summary of current figures worldwide – please see Qureca's [Overview of quantum initiatives worldwide](#)

Much has been written about the world's quantum programmes by experts around the world [1; 2; 3; 4; 5; 6; 7; 8]. This article focusses on key developments in 2020, and what they tell us to look out for in 2021. In support of its views, Fact Based Insight can only offer its independence, having not taken or sought funding from any of these programmes.

Europe

The EU Commission has realised the important future role of quantum technology. In addition to the formal [QT Flagship](#) programme, it has considerably enhanced the resources available by aligning spending from other programmes such as its Digital and Space programmes. The long term aim of 'building the Quantum Internet' has proved a powerful unifying vision across the QT Flagship, which in 2020 published its strategic research agenda [9].

Quantum spending in the EU, across the QT Flagship, EuroQCI, OpenQKD and related programmes is already estimated to be €3-4b over 10 years.

The QT Flagship projects are certainly living up to their name. They have clearly stimulated collaboration not just within each individual project consortium, but also across projects. They are also delivering win-win synergies with national quantum programmes. 60 patent applications are associated with Flagship projects (an area where Europe has been concerned it is weak). Events such as the excellent European Quantum Week have helped build their profile and provided a model for transparent update on progress [10].

QT Flagship – The 19 projects of the [ramp-up phase](#) of the programme are spread across quantum computing, communications, simulation, sensing & [metrology](#), and basic science. 2020 saw these projects pass their mid-term review [11]. Two new projects were launched in 2020, QLSI adds silicon spin qubits to the superconducting and trapped ion qubits already being targeted; NEASQC specifically targets [NISQ](#) applications and starts to address the balance of a programme that many felt was short on software focus [12].

Work-in-progress – Fact Based Insight was impressed by the results on show at European Quantum Week. The programme has mobilised from a physics-dominated base. Moving beyond that to bring in more engineering, computer science and maths talent is an opportunity the programme is working on.

EuroQCI brings together 25 EU states, the Commission and the European Space Agency with the specific aim of building a pan-European quantum communication infrastructure. This envisages two key elements to be deployed within 10 years: ground based systems using existing fibre links between strategic sites and space based links for long distances and remote locations. The first service is envisaged to be [QKD](#), but other services will follow such as digital signatures, [authentication](#), and the synchronisation of ultraprecise time signals. Thierry Breton (EU Commissioner and former ATOS CEO) places emphasis on important secondary goals "It will also lead to the development of a world-class quantum communication technologies industry in Europe, boosting our technological

sovereignty in this key area” [13]. OpenQKD complements this initiative by providing testbeds to demonstrate a wide variety of client use cases.

[HPC](#) – Quantum computing also explicitly dovetails into the Commission’s vision to defend Europe’s position in HPC. Breton is specific “Our objective is to rapidly reach the next standard of computing with exascale computers – but also and foremost to *already* integrate quantum accelerators to develop hybrid machines and position Europe very early on this disruptive technology.” [14]

Ensuring Europe’s successful ‘digital transition’ is a key policy objective for the EU. This is supported by the EU’s research & innovation programme, [Horizon 2020](#) (2014-20) which is set to be succeeded by [Horizon Europe](#) (2021-27). This is where the QT Flagship is principally funded from, and it is seen as a priority within the digital agenda [10].

The programme does face headwinds. Brexit, the COVID-19 crisis and the drift to the popular right in some central European states has created a perfect storm for the EU budgetary process. The Commission’s proposal for a very much expanded budget for Horizon Europe had to be dramatically scaled back. This doesn’t threaten the programme as it stands, but it limits scope for the substantial increase in funding that many would like to see. To mitigate this the Commission can be expected to seek to align funding from other sources behind the objectives of the programme.

European research programmes have traditionally championed the values of open science, open innovation and open to the world. Associated membership has allowed non-EU states to participate, and the [QuantERA](#) funding mechanism has proved a flexible tool for encouraging collaboration around the wider European research area. As such, the QT Flagship is currently exploring potential collaborations with Canada, Japan and the US [10]. However securing digital or technological sovereignty is an increasingly important part of EU aims. This includes limiting dependence and influence from both Chinese and American interests [15]. This has created some uncertainty over how inclusive and flexible future programmes can be.

In common with other quantum programmes workforce development is a major area of focus. However, here a key related question does not seem to have a clear answer – is the objective to persuade talented European students not to go to work at Alphabet and Alibaba, or is it to persuade such international tech majors to base more of their high value development activities in Europe?

Business participation – a number of large European businesses are actively engaged with the QT Flagship, notably ATOS, Thales, Airbus, Volkswagen, Bosch and EDF. However many still look for a shift in wider European business attitudes. Jurgen Mlynek (QT Flagship SAB chair) comments “US tech companies are more willing to invest for the long term. Big European companies say ‘nice to hear what you are doing, but we are a technology taker rather than a technology maker, please contact us when you have something.’” [10]

QuIC – Preparations are advancing to launch a European Quantum Industry Consortium. This is seen as a counterpart to the US [QED-C](#) that has been an early success of the US programme. Target membership could be 200-225 members. [16]

On another specific point, EU wide initiatives have naturally struggled. Many believe that neighbourhoods in the future quantum ecosystem will be anchored around specific geographic locations. The success of Silicon Valley in the US is the archetypal example. Rather than looking to EU programmes to directly develop such centres, perhaps it's more realistic to look for them to organically grow out of national initiatives.

Many European states have significant quantum activities, including Austria, Spain, Hungary, Poland, Sweden and others. However three EU states, and one former EU state stand out for further examination.

Germany

The German government has announced that it will spend €2b of its COVID-19 recovery fund on quantum technology research [17]. This comes on top of the €650m earmarked for spending between 2018-22. The German EU presidency of H2 2020 again put the emphasis on the important role of quantum technology in ensuring technological and data sovereignty. Germany has already introduced tighter restrictions on the take-over of high tech firms, including quantum technology firms, by non-EU interests.

Germany already has powerful building blocks such as the Max Planck research Institutes, the Helmholtz Association and Fraunhofer, a leading [RTO](#) already involved in quantum technologies projects in multiple countries in its own right.

Forschungszentrum Jülich increasingly looks like a rising destination on the European Quantum grand tour. Already a major multidisciplinary research centre across physics, chemistry, biology, medicine and engineering and a major supercomputer centre, it has launched JUNIQ to provide a platform for access to multiple quantum computing technologies. In 2021 it will be the initial HQ of the EU QuIC and to host the initial quantum computer delivered by OpenSuperQ. It is set to host the Helmholtz Quantum Center (HQC) which should be fully operational by 2025.

MCQST is setting out to build a Munich Quantum Valley. It already enjoys €120m support over the next 2 years from the Bavarian State. PlanQK is emerging as a virtual quantum software cluster. Notable early movers from German industry include Volkswagen and Bosch.

The Netherlands

The Netherlands is already a key centre of quantum activity. QuTech was founded back in 2014 and already has 'national icon' status. It boasts strong industry connections with majors such as Microsoft and Intel, key specialists such as BlueFors and interesting startups such as Orange Quantum Systems, Qblox, Single Quantum and Delft Circuits.

The Quantum Delta NL (QΔNL) programme is bringing increased coordination and investment across other already strong components: QuSoft (software), QT/e (materials), TNO (an RTO) and multiple strong universities. Activities are organised around five city based hubs in three main catalyst programmes: quantum computing and simulation, national quantum internet, and quantum sensing applications. [18]

The Netherlands makes no bones about wanting to position itself as 'the quantum gateway to Europe' and to build the Silicon Valley of Quantum, emphasising its central compact location, the high ease of doing business

and great quality of life. Its fruitful and ongoing relationships with Microsoft and Intel certainly back this up, while it has also been able to benefit from close involvement in QT Flagship projects such as QIA and iqClock. Quantum Inspire (launched as part of the computing catalyst programme) seized a notable milestone in 2020 as the first European-based quantum cloud platform [19].

France

France already benefits from three pronounced clusters of quantum sector and associated high-tech industry expertise. Large businesses with strong French connections are already prominently engaged in the quantum sector, such as ATOS, Thales and Airbus.

Paris-Centre boasts [PCQC](#) as well as notable startups Alice & Bob, C12, Veriqloud, [Qubit](#) Pharmaceuticals and QC Ware France.

Paris-Saclay has launched Quantum, an interdisciplinary centre for quantum science and technology.

Grenoble boasts Quantum Engineering Grenoble and Quantum Silicon Grenoble and also leverages the strengths of [CEA-Leti](#) and CNRS-NEEL. Expertise in [CMOS](#) processes and cryogenic CMOS electronics makes it a natural option for developing silicon spin technology in particular.

At the beginning of 2020 France launched a top level Quantum Plan [20]. Details of the roadmap have been delayed due to the COVID-19 crisis and are still to emerge. Further investment in each of its existing quantum hubs is likely.

Vive la France – It's tempting to point out that both the QT Flagship projects launched in 2020 seem to have been strongly lobbied for by French voices. However, Fact Based Insight also believes that there was a strong case for each on its own merits.

United Kingdom

The UK's [NQTP](#) is widely respected as being the first quantum technology programme in the world to target the economic opportunity of the sector in its widest sense, co-ordinated across quantum computing, communications, timing, sensing and imaging [21]. This model has now been almost universally copied in quantum-active nations around the world. In 2020 an updated strategic intent has been published [22].

Spending of NQTP phase 1 & 2, including public and private sources, is already set to be about £1b for 2014-24.

Many look to the UK programme, not just to gauge the progress of quantum tech in the UK, but to learn lessons that may help their own plans.

NQTP Phase 1 (2014-19) was dominated by four academically-led hubs, focussing on networked quantum computing, quantum communications, quantum enhanced imaging, and quantum timing & sensing. The NPL also had a unique role to play due to its strong metrological expertise. The projects undertaken already went beyond traditional pure science, and focussed on how that science was to be applied.

Results – the initial phase delivered a series of great proof of principle and demonstrator projects. It also mobilised the community and built a habit of academic/industry collaboration. Its original scope was built on UK strength in photonics, a key enabling technology across all quantum pillars. However a notable success of the programme has been it moving out beyond the physicists, to also draw in engineers. The vibrancy of the UK quantum software scene is second to none and benefits from having brought in maths and computer science talent. Fact Based Insight sees the contribution of traditional university networks in this interdisciplinary success. NQPT phase 1 didn't deliver on all its product aspirations, not really, but that was never an appropriate expectation for this type of R&D.

NQTP Phase 2 (2019-24) has moved the emphasis and resources sharply onto commercially led projects. As products have edged closer to market, industrial partners have typically wanted more control over shaping and leading initiatives, while still benefiting from the collaborative framework that the programme provides. In response, [Innovate UK](#) has used the [ISCF](#) to launch waves of projects with mixed public/private funding to support and develop the growing quantum ecosystem.

Work-in-progress – The Innovate UK team has a strong emphasis on programme management and strengthening the commercial presentation of programme initiatives. However this is not a conventional task – the team is still clear that “if all the projects work, then they are funding the wrong projects.”

The research programmes of the original hubs also continue. The focus has now moved distinctly up the quantum value chain. A focus on single [quanta](#) and [superposition](#) has given way to a focus on the possibilities offered by quantum [entanglement](#).

Imaging – The UK programme continues to allot quantum enhanced imaging its own pillar of activity. Most others worldwide simply group this with sensors. The UK approach has helped it target the relatively near-market opportunities in this segment. It has also helped stimulate the underlying quantum photonics ecosystem and develop important computational techniques in sensing.

The [NQCC](#) is another major feature of phase 2. The centre is not envisaged as another direct competitor in the quantum computing race, but as a facility to accelerate the work of the community (and to make sure it sees the UK as an attractive place to base R&D for the long term).

Ramp-up – The design of the physical centre is now complete and construction will run through 2021-22 with facility handover in Q1 2023. Initially the centre has identified superconducting qubits, trapped ions and software as high priority areas, but it's an investment in quantum computing not a specific qubit technology. [23]

ISCF is currently funding over 40 quantum sector projects launched over three waves. Typically each consortium brings together 3-10 partners from across the supply chain with strong academic support. Projects are typically set to run 18-36 months with a budget between £0.5-10m. The flexibility of this approach means that complementary and follow-on projects can be developed over time. Overlaps also exist where different projects could ultimately lead to competing products. A range of project types are supported. [24]

Feasibility studies – Typically smaller projects, for example the Gravity Delve initiative to explore the use of quantum gravity sensors in harsh borehole environments, which itself exists in parallel with ABGRAV another gravity sensor initiative.

Collaborative R&D – Larger projects that bring together supply chain players to advance a product prototype. The emphasis is often on ensuring a viable supply chain is in place to support the commercialisation of a prototype, and that input can be taken from likely lead users. Examples include KAIROS, a Teledyne e2v led initiative to commercialise a compact atomic clock, or the Rigetti-led initiative to build a quantum computer in the UK.

Technology projects – Larger projects to put in place capabilities required by the wider ecosystem. This focus allows new supporting infrastructure to be put in place. Examples include Quantum Foundry, an OQC led initiative to put in place fabrication and measurement facilities, and Deltaflow.OS, a Riverland led initiative to provide a hardware agnostic software stack.

Workforce education is another continuing point of emphasis in the UK programme. To enhance the flow of graduates with appropriate advanced degrees, Centres for Doctoral training have promoted key disciplines in quantum technology and quantum systems engineering.

[QTEC](#) was a unique initiative in UK NQPT phase 1 seeking to address the challenge of turning scientists into entrepreneurs. ‘Fellowships’ supported early career stage researchers with a salary, expenses, business training and mentoring for a year while they worked on the launch of their business idea. Former QTEC fellows are now involved in rising stars of the quantum sector such as KETS and Seeqc, or have made impressive progress commercialising sector specific applications such as QLM or FluoretiQ. Nu Quantum and Quantum Dice are two notable more recent startups.

Fact Based Insight believes that QTEC has been a clear and obvious success. However its continuation isn't currently funded in phase 2 of the NQTP. Its original funder was the [EPSRC](#) the usual port of call for university based activities. But the EPSRC's core mission is rightly focussed on scientific research and training. Meanwhile Innovate UK has been running hard to launch the big wave of ISCF projects that business partners in the programme so strongly desired. Fact Based Insight hopes that the NQTP will find a way to move the entrepreneurial pillar back up the agenda.

The NQTP's new strategic vision wants to make the UK the 'go-to' place for quantum enterprise and quantum talent. An early opportunity that got away was PsiQ which adopted the US as its home even though many in the senior team had strong UK-links. Now in phase 2 the UK programme has seen notable successes. US based players such as Rigetti and ColdQuanta have been attracted to lead in significant projects in the UK. Teledyne e2v and Hitachi have used their UK subsidiaries as a vehicle to expand their R&D in the sector. Toshiba is basing the manufacture of its initial QKD equipment in the UK. A vibrant startup scene has formed. The announcement that BAE, BT and BP, three FTSE 100 companies, will collaborate to define a quantum sensor roadmap carries extra weight because these businesses have already built significant practical quantum experience rather than just blue sky thinking [25].

Horizon Europe – The UK's continued participation, or not, in the EU's premier research programme is a major uncertainty hanging over the community.

UK research has traditionally done well in terms of the share of funding received from European research programmes. Perhaps even more importantly it has been well placed to benefit from the network of research relationships established.

The UK NQTP pre-dates the QT Flagship, and was a key inspiration for it. But any exposure to the NQTP quickly highlights the central role played by many continental European nationals, and patterns of cross-collaboration on current QT Flagship projects provides numerous examples of why this is a win-win. On the other hand, the UK presence in the leadership of QT Flagship is now marginal. Without Brexit it would probably have been central.

The UK government has consistently declared that it would like to take part in Horizon Europe. EU research leaders are also strongly seeking this outcome. Unfortunately the logic of trade negotiations between the EU and UK over a post-Brexit deal has left the future of UK participation in Horizon Europe mired in uncertainty [26].

Both the UK NQTP *and* the QT Flagship will suffer if they can't make continued collaboration work.

(Editor: since this article was originally published, the terms of the post-Brexit trade deal between the UK and EU have preserved UK participation in Horizon Europe. This is welcome news for both quantum programmes, though the challenge of maintaining the momentum of future collaboration remains.)

The UK continues to have strong research relationships around the wider world. A keynote at the 2020 National QT Showcase was the announcement of a joint Canada/UK funding round. Though small in cash terms, this is notable as the first multi-regional initiative aimed at supporting the *commercialisation* of quantum technology, rather than the less contentious area of basic research. [27]

Fact Based Insight believes the stage is now set for a further acceleration of quantum funding in the UK.

A notable plank in Prime Minister Boris Johnson's manifesto was a plan for a major increase in public R&D spending and the creation of a new agency for high-risk, high-payoff research – a British [ARPA](#). However, debate has continued about how exactly such a BARPA should be constituted, and in particular its relationship with [UKRI](#). UKRI is itself a relatively recent creation that brought together the UK's main research funding organisations including the EPSRC and Innovate UK, who together have been the principle funding vehicles for the UK NQTP (indeed the structure of the NQTP foreshadowed this change).

Hard core proponents of BARPA, including Dominic Cummings (the now departed chief prime ministerial advisor) had wanted to see it as a new arms-length agency outside of current structures. Other voices, including Jo Johnson (Former Science Minister and brother of the PM) and Mark Walport (co-father of the UK NQTP and former head of UKRI) argued that UKRI would be an ideal place to 'incubate an ARPA-like body' [28]. The recent post-COVID UK spending review has tilted in this latter direction. The success of the NQTP will have been no small part of securing this victory. The UKRI core research budget will now increase by £400m per year for the next three years. In addition the first £50m from a high-risk, high-payoff fund is to be spent by UKRI in 2021-22, with a total of £800m of this additional provision to be spent by 2024-25 [29]. Not all of this new funding will be spent in the quantum sector, but it can be expected to capture a significant share.

North America

Canada

Canada has a prominent history in modern quantum science. Notably in 1984 Giles Brassard (Univ. Montréal) was co-author of the famous [BB84](#) quantum [cryptographic](#) protocol. In 2002 the pioneering Institute of

Quantum Computing ([IQC](#)) was founded at the Univ. Waterloo.

Between 2008-2018 over C\$1b was invested in quantum science and technology.

In 2017 Canada's [NRC](#) launched a program called Quantum Canada. For a country of its size the number of high profile quantum sector companies headquartered in, or with strong links to, Canada is impressive. Notable examples include D-Wave, Xanadu, 1QBit, Quantum Benchmark, evolutionQ, Zapata and ISARA. Creative Destruction Lab has been a notable accelerator for quantum sector startups.

Waterloo's 'Quantum Valley' is building out a tech cluster around the established strength of the IQC and the Perimeter Institute. Notable supports for this ecosystem already include Quantum Valley Investments and the Quantum Valley Ideas Lab. [\[30\]](#)

In 2020, this was consolidated by the formation of a new industry consortium, Quantum Industry Canada [\[31\]](#). 2020 has also seen C\$153m of co-investment funding announced for the Digital Technology Supercluster in Vancouver, British Columbia [\[32\]](#).

United States

The US has a long history of investment in quantum science. Only more recently has this been consolidated by a nationally co-ordinated programme. 2020 was the second year of the US [NQI](#) [\[33\]](#) and saw important developments as the programme really took specific shape.

The NQI authorised spending of \$1.3b for 2019-2023. Significant additional private funds are already being invested.

The [NSF](#) established three new Quantum Leap Challenge Institutes. These academically led hubs will support programmes of research in distinct areas. [\[34\]](#)

Q-SEnSE – Quantum Systems through Entangled Science and Engineering (led by Univ. of Colorado Boulder). Will develop advanced quantum sensing for new fundamental physics and novel quantum technologies.

HQAN – Hybrid Quantum Architectures and Networks (led by Univ. of Illinois' IQUIST). Will develop multi-node testbeds for trapped ion, neutral atom and superconducting qubit systems, together with a distributed quantum computing software stack. Also working on next-generation protected qubits. Close links to the Chicago Quantum Exchange.

PFQC – Present and Future Quantum Computing (led by UC Berkeley). Theoretical research on quantum algorithms for early NISQ devices through to large scale [FTQC](#).

The [DOE](#) runs a unique network of 17 national laboratories that give it unique capabilities in the US research landscape. The DOE has launched five National QIS Research Centers. [\[35\]](#)

Q-NEXT – Next generation quantum science and engineering (Argonne National Lab). Will focus on long distance quantum networks, quantum-enabled sensing, and processing & testing. It will establish two national quantum foundries for materials and device fabrication. Intel, IBM, Microsoft and ColdQuanta are notable partners.

C2QA – Co-design center for [quantum advantage](#) (Brookhaven National Lab). Aims to overcome the limitations of early NISQ devices to achieve quantum advantage for scientific applications in high-energy, nuclear, chemical and condensed matter physics. The 5-year goal is a factor of 10 improvement in each of software optimization, underlying materials and device properties, and quantum error correction. The target is a combined factor of 1,000 appropriate computation metrics. IBM is a notable partner.

SQMS – Superconducting Quantum Materials and Systems Center (Fermi National Accelerator Lab). Will focus on creating better superconducting qubits by understanding the physical processes that cause decoherence. Aim to build a quantum computer with next generation superconducting qubit technology. Rigetti is a notable partner.

QSA – Quantum Systems Accelerator (Lawrence Berkeley National Lab). Aims to co-design the algorithms, devices and engineering solutions needed to deliver certified quantum advantage in scientific applications. Focus technologies include neutral atoms, trapped ions and superconducting qubits. Sandia National Laboratories is the lead partner. A notable feature is the international coordination board with representation from Germany, UK, Australia, Austria and Japan.

QSC– Quantum Science Center (Oak Ridge National Lab). Discovery, design and demonstration of topological quantum materials, algorithms that exploit topological systems, and new quantum systems to measure exceptionally weak signals. Microsoft is one of five core founding members. IBM and ColdQuanta are also notable partners.

Each of the institutes also emphasise the role they will play in training and workforce development. In addition, the National Q-12 Education Partnership is a plan to work to put in place improved quantum learning across all educational centres.

[NIST](#) is another key part of the US programme. Metrology is now intrinsically linked to quantum science. NIST is naturally at the forefront of research in many high-performance quantum technologies (notably in trapped ions and quantum clocks). A key activity by NIST has been supporting the creation of QED-C.

QED-C is a consortium of stakeholders with the mission to enable and grow the quantum industry and the associated supply chain. The industry-driven consortium is managed by SRI International and supported by government and more than 160 corporate members from industry, universities, and national labs. QED-C brings together experts from all parts of the quantum ecosystem to identify and help to fill gaps in enabling technologies, standards and metrics, and workforce.

QED-C will continue to identify enabling technology gaps and work with government and industry partners to fill those gaps. A key question will be what role there is for international partners. The QED-C is certainly keen to engage. Celia Merzbacher (QED-C Deputy Director) emphasises “QED-C members envision the quantum supply chain as a global network and we will be offering non-US membership options in 2021”. QED-C can also be expected to keep a key focus on building a diverse supply of talent coming into the industry (including from minority serving institutions).

Overall co-ordination for the US programme comes from the White House National Quantum Coordination Office (NQCO), and strategic guidance from the National Quantum Initiative Advisory Committee (NQIAC). This

has been able to bring together an enviable combination of inputs from big tech, national laboratories and leading scientists across the quantum sector.

The NQI enjoys bipartisan support. It's particularly notable to recall that then senator Kamala Harris was the primary sponsor of an early alternative approach, the Quantum Computing Research Act. This envisaged a Defence-led quantum consortium. Continuing DOD and National Intelligence quantum programmes are already an important part of the US quantum landscape. The national security potential of quantum technologies is also a theme that has been emphasised by QED-C.

[AFRL](#) – The respected Airforce Research Lab has been an early mover on the US quantum scene. It boasts a large and joined-up programme across timing, sensing, communications and computing (algorithms). It's also notable for initiatives reaching out and drawing in the wider technology innovation community, such as AFWERX and its Quantum Collider events. [36]

[DARPA](#) – The legendary status of this research agency, and its predecessor ARPA, has granted it almost cult status in the deep tech community. Past programmes have already been influential in the early development of quantum tech, notably CSAC (2001-9) for atomic clocks, QuASAR (2010-18) for quantum sensing; QuIST (2001-5) in quantum computing and communications (including demonstration of the world's first QKD network). Notable current programmes include ONISQ to create a NISQ quantum computer, and TEE to develop materials with unique topological properties, for use as topological qubits among other potential applications. Notable research partners include Rigetti and ColdQuanta. [37]

[IARPA](#) – Itself inspired by ARPA, this agency has had a number of influential quantum programmes, including CSQ (2009-14) superconducting qubit technology; MQCO (2010-15) scaling challenges; QCS (2010-13) resource benchmarks for key algorithms. Current programmes include LogiQ (2015+) on the development of logical qubits; and QEO (2016+) on coherent quantum annealing. Notable research partners include IBM. [38]

A striking feature of the early strategic direction of the programme has been the emphasis it has placed on the role of quantum networks in securing maximum value from the quantum revolution [39]. This has been followed-up by the DOE's launch of a blueprint strategy for the development of a national US Quantum Internet based on an initial backbone linking the DOE's 17 national labs [40].

To achieve these wider objectives two more bills were put before Congress in 2020. These didn't pass, but might be expected to be reintroduced. With new leadership at the relevant agencies (for example DOE), new players in the Congress, and the Senate balance still to be decided by a run-off election, it is difficult to be certain how this will play out.

Quantum Network Infrastructure Act – To accelerate R&D underpinning the US quantum network – \$500m over 5 years. [41]

Quantum User Expansion for Science and Technology (QUEST) Act – To support research access to quantum computing resources – \$340m over 5 years. [42]

While broad, the US programme has made choices. Next generation superconducting qubit technology is a distinct focus, followed closely by trapped ion and neutral atom platforms. Topological qubits get their own distinct programme. By contrast silicon spin and photonic computing approaches are relatively absent. Specific focuses for algorithms and software platforms are also evident, as are multiple strands on quantum sensing. However, despite the emerging emphasis on the role of quantum networks, only one of eight institutes/centers picks up this role. Without additional funding this could start to appear an imbalance.

The emphasis placed by many of the new institutes and research centers also retains a notable strand of emphasis on scientific applications. This can be justified on the grounds that these are indeed real applications and the past has taught us on many occasions that advanced techniques pioneered for scientific applications then migrate to wider uses. However this does represent a potential source of frustration by industrial partners (as we saw in phase 1 of the UK programme) who will in some cases differ with academic colleagues on project priorities.

The NQI programme is now fully up and running. It builds on strong foundations and we can expect a further acceleration of exciting progress in the years ahead.

A key question many will be asking is to what extent the US programme will work with international partners to achieve its objectives.

China

Driving China's rising prominence in science and technology has been a continuing theme of successive Five Year plans (and in particular, since 2006, including quantum science). Over \$1.5b of central and province funds have already been spent [8]. USTC in Hefei has emerged as a major world leading centre for quantum research. China has by far the world's largest deployed QKD networks and continues to lead the world in the demonstration of increasingly advanced quantum communication technologies from space. The Micius satellite [43] and Jiuzhang quantum processor [44] are flagship successes of the programme.

Spending in China's programme was \$1b from central funds and \$500m from regional funds 2006-20. State media has reported the investment will reach almost \$15b (100 billion yuan) by 2022, though details of what this means are not available. [45]

A network of National Laboratories of Quantum Information Science ([NLQIS](#)) is being created. [46]

NLQIS Hefei – Set to be the world's largest quantum research facility and an overall HQ for the programme. This location will focus on photonic, NV diamond and silicon spin qubit technology as well as quantum communications and quantum sensing.

NLQIS Beijing – this branch will focus on theory, trapped ion and topological qubits.

NLQIS Shanghai – this branch will focus on superconducting qubits and ultra-cold atoms, and free-space quantum communication.

China's national quantum network continues to develop with a focus to make it safer, faster and wider. [46]

Longitudinal backbone – The original 2000km Beijing-Shanghai link is being extended with 5500km of additional links currently under construction.

Transverse backbone – In addition 700km of an additional transverse backbone is already complete between Hefei and Wuhan, with an additional 360km under construction and 2200km proposed.

Satellite – Advanced programme to develop a constellation of QKD enabled nano satellites.

Alibaba, Baidu, Tencent and Huawei all have quantum investments in quantum technology. QuantumCTek and Origin Quantum are notable startups.

14th Five Year plan – 2020 saw details emerge of the plan which is expected to be formally adopted in 2021. A key concept is 'dual circulation'. This involves reducing reliance on foreign high-tech and foreign demand, though it also promises increased opening to foreign investment. Innovation is also a key theme (mentioned 47 times in the draft proposal). [47]

Quantum technology will explicitly be one of the key high tech focusses. It was notable that in the run-up to the launch of the draft, President Xi Jinping took the opportunity to personally stress the importance and urgency of advancing quantum science and technology. The continued development of China's AI and aerospace programmes are also continuing and complementary strands [48]. In a development that suits the long-term horizons of quantum technology, the 'Five Year' plan is increasingly a roadmap all the way to 2035.

China Standard 2035 – one aim in the 14th Five Year plan is to build Chinese leadership in setting common specifications for leading technology. This has very direct relevance to quantum technology where a first wave of important standards is currently under discussion and many more will follow.

The case for standards is that they provide a level playing field on which interoperability and a common global marketplace can be built. However any sports coach will tell you that no playing field is truly level. China's engagement with current international standard setting bodies is positive, but it has recently caused some concern. Participation in recent [ITU-T](#) quantum working groups has often seen 20+ participants from China working with perhaps 10 from Europe and 5 from North America.

Other highlights from around the world

Australia

Australia has very strong quantum sector activities, notably including [EQUUS](#) and [CQC2T](#). A diverse base of quantum startups have formed, including notably UNSW spinouts SQC and Q-CTRL as well as QuintessenceLabs.

Almost uniquely among major quantum nations, Australia doesn't have a national programme. However in 2020 CSIRO set out a strategy for Growing Australia's Quantum Technology Industry [49]. The Australian

Quantum Technology Forum (AusQuantech) has been formed to unify the sector and promote its development [50].

Japan

The [Q-LEAP](#) flagship programme was launched in 2018. The [JST Mirai](#) programme also has strong quantum sensor and clock links. [SIP2](#) has strong links with quantum software and quantum cryptography. A Quantum Technology and Innovation Strategy was finalised at the beginning of 2020. Priority research areas include quantum computing, communications and sensing. Research hubs are being launched and international collaboration sought with the EU and US. [46]

Notable flagship initiatives include a superconducting qubit NISQ computer and a NISQ software programme. Japan also has a separate programme for Moonshot R&D investments. One goal here is the development of a fault tolerant quantum computer by 2050. [46]

Russia

[RQC](#) was founded in 2010. Over the last 18 months work has been ongoing to define a strategic plan for Russia's future quantum activities. In 2020 this has emerged as three separate roadmaps, each for a different quantum pillar. In an interesting approach, each pillar is led by a major Russian state owned company: Rosatom is responsible for quantum computing and simulation; Russian Railways is responsible for quantum communication; Rostec is responsible for quantum sensing & metrology. [46]

Singapore

[CQT](#) was established in 2007 and benefits from long standing government support and its wide international collaboration base. In 2020 it initiated a new 5 year Quantum Engineering Programme. A thriving group of quantum startups has formed. Quantum SG has been created as a focus for this community, and has published 'Quantum Technologies in Singapore – preparing for the future'. [51]

Global academic co-operation

The new US administration will seek a reset in American relations abroad, but most expect the relationship between China and the US to remain tense. It is unlikely that president Biden will continue the confrontational language of his predecessor, but he will still likely see China as a competitor in an intensifying global technological race.

Fear of being overtaken by China was used in no small part to mobilise support behind the NQI. In Europe, the EU's quantum programme and Germany's large new initiative see securing quantum technological sovereignty as a key objective. China's emphasis on dual circulation places a strong emphasis on technological self-reliance. The increasing commercialisation of quantum technology is also increasingly drawing leading researchers into corporate jobs where ultimately the shutters will come down on openly

sharing research results. The presence of Chinese research students in western institutions has recently become much more politically contentious.

However, there are efforts to keep the lines of global scientific discourse open. The most notable academically focused conference of the last year was Quantum 2020, jointly organised by the IOP and the Chinese Physical Society. This featured cutting edge contributions from all quantum sectors and from across all the main quantum research nations.

Jie Zhang (President of Chinese Physical Society) opened Quantum 2020 with a call invoking the spirit of international scientific collaboration and exchange. Speaking on a notably broad and high-level panel on international quantum technology programmes, Tommaso Calarco (Chair of the EU Quantum Community Network) took up the call for a response to help the community remain inclusive. Sir Peter Knight (a father of the UK NQTP) used the panel to advance the idea of a 'Quantum Alliance' of learned societies around the world to ensure continued dialogue and where possible openness on matters of basic science. Such ideas are likely to chime widely with academics around the world. [46]

Many old commercial hands may dismiss the role of such traditional academic ideals. However it's commonplace to point out that the ultimate key driver of future quantum success will be the quality of the quantum workforce that you can build. It's that workforce that is the key output of our universities. Increasingly our ability to inspire and retain that talent could be down to the values our societies and companies represent.

What season for quantum investment?

One reason behind generous government programme support is fear that, left to its own devices, commercial investment may not be sufficient to see the quantum revolution over the line. At least not on the timelines (and in the locations) governments might prefer.

At one level, 2020 was a record year for venture capital invested in quantum tech with QIS Data from Interference Advisors reporting \$1,040m (to mid Nov [52]). Though as they point out, fully half of this was from just two deals, PsiQ and XTalPi (and though the latter may be a great business, many would not see it as a 2QR business in the normal sense). Several high profile quantum hardware players are also reported to have taken down-rounds in 2020. The contrasts are also striking. Quantum cryptography has attracted only modest new venture backing in the West, while QuantumCTek set a first day market record with its Shanghai IPO [53]. Venture backing for quantum sensing has barely registered.

The uncertainties are very real. However there are strategies to balance this risk. Quantum hardware, software, communication and sensing are linked by many common enabling technologies and skill sets. Importantly they are not commercially in sync, either in the degree of hype they bear or in the timelines they offer to real world revenues. So far only Quantonation really stands out as a portfolio investor ready to champion this insight.

Community comment currently points to a sector where many big investors are content to hold their positions and wait for the promised progress. Venture funds are cautiously picking only a small number of projects to back. The disruption brought by COVID-19 has been very real. At the moment, backing from large corporate pockets or government programmes is the easiest route for many.

Those with deep roots in the sector are well aware of where current activity and expectations have run ahead of what theory can prove about the capabilities of today's early devices. At Q2B, John Preskill (Caltech) commented about a fear many have for the coming years "a quantum computing winter is a real possibility and a serious concern". [54]

Equally, today's brave pioneers may start to fill in the blanks whether the theorists have stumbled. There are plenty of very bright people working to do just that in 2021. Quantum investors must be ready to dress for all seasons.

To watch in 2020

- China's 14th Five-Year Plan – The success of Micius and Jiuzhang have been huge birthday presents in advance of the CCP's 100th birthday. Expect 'shock and awe' as details emerge on just how much China will now plan to invest in quantum, AI and space based tech. The plan will be formally approved by the National People's Congress in March 2021.
- European Spend – An increasing number of individual European countries have their own significant programmes. Could we see investment across Europe top €8-9b for the next 7-8 years? Watch out as specific details of Germany's programme emerge; watch out for the appointment of France's National Programme Director and for its detailed roadmap to emerge. Will we see a truly complementary fit?
- Horizon Europe – How will international participation in Horizon Europe develop? Will terms be found on which the UK can participate? (*Editor: we now know the UK will participate; might Canada or Japan also be enticed to join?*)
- QT Flagship – As the dust settles on the final EU budget deal for 2021-27, look out for funding news on the next wave of European quantum projects. How far will the programme build-out from its physics core?
- Quantum consortia – QuIC is a group forming in the hinterland of the QT Flagship; EQIC is a group forming under the auspices of EPIC, the European photonics industry association. Will these groupings manage to align or combine their efforts? What can they help their members do together? Watch out for the impact of similar groupings in Canada, Australia and Singapore.
- CERN, ITER or AIRBUS – Europe has thrown-up a number of models for large scale scientific, research or commercial collaboration. Watch out for debate on which model is best suited to a big initiative in quantum tech.
- Lawful intercept – The EU is increasingly seen as a global leader on matters of data privacy law. Many EU politicians also want to protect the right of 'lawful intercept'. How will this be reconciled with plans for a genuine entanglement-based Quantum Internet?
- UK – Watch out for further quantum projects funded through ISCF and the new high-risk, high-reward initiative. Can the UK mobilise the partnership and resources to retain its competitive position in quantum?

- Japan – Expect quantum tech to feature strongly in Japan's 6th Science and Technology Basic Plan (2021-26) due to be approved early 2021.
- Russia – Watch for details of the Rosatom, Russian Railways and Rostec led roadmaps.
- US – With three new NSF institutes and five new DOE research centers, watch out for a blizzard of quantum sector work launching in the US. Will the programme be able to demonstrate it is more than the sum of its parts?
- US Congress – Watch for progress on the QUEST Act and Quantum Network Infrastructure Act. Will these extensions of NQI be reintroduced and pass in the new Congress?
- Global supply chains – Watch out for interest in the QED-C's new membership tier for non-US companies – who will join?
- International collaboration – The EU is seeking technological sovereignty. The Biden presidency promises to mend fences. China is choosing to turn inwards. Others are looking for partners. Watch out as patterns of international collaboration develop in commercially sensitive and dual-use technology areas. Japan, Canada, Australia and Singapore are all notable dance partners. The UK NQTP may be the jewel in the crown.

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