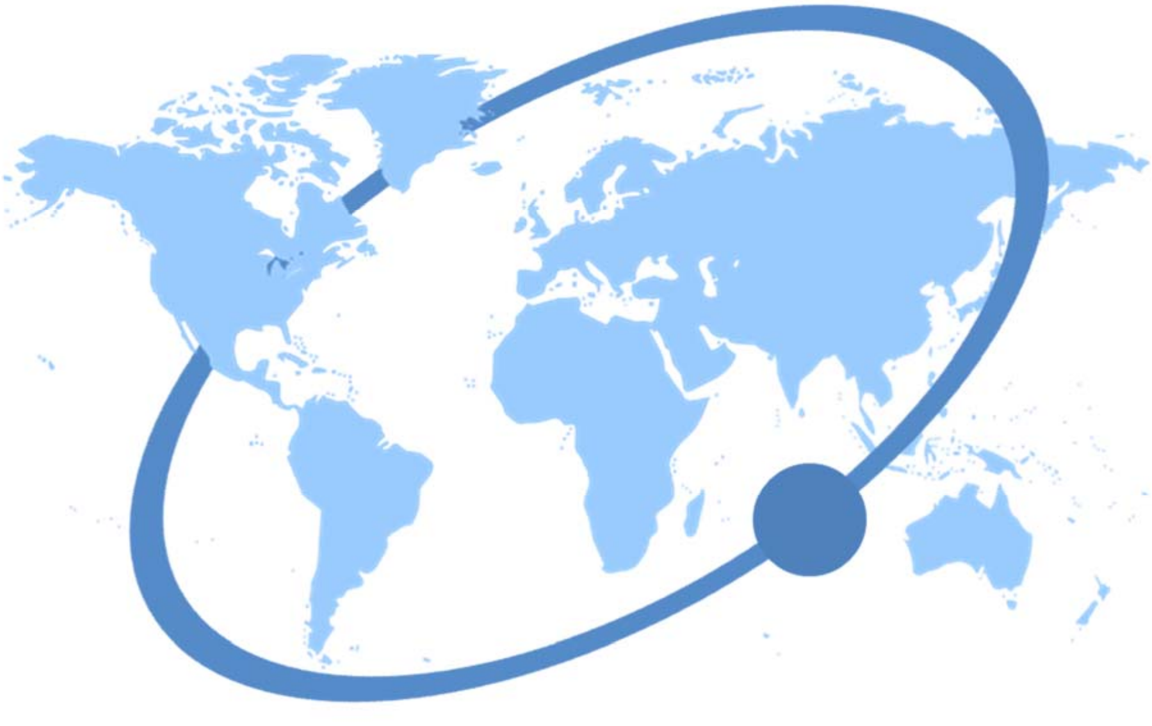
A Review of International Approaches to Supporting

Quantum Technologies Research & Innovation



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This review of quantum technologies, at the behest of the Engineering & Physical Sciences Research Council (EPSRC), will present international approaches to fostering the development of quantum technologies (QT), and is intended to provide evidence that will inform the development of policy relating to future UK QT strategy.

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1 Introduction

This interim report provides an initial overview of international approaches to public support of quantum technology (QT) research and innovation. In particular, this report examines national research strategies and major funding programmes related to quantum technologies. The analysis pays particular attention to efforts to translate applied scientific knowledge into engineered platform technologies and application-system demonstrators (including efforts to address the 'manufacturability' and industrialisation challenges of quantum technologies). The report also explores any efforts at cross-government coordination around QT and initiatives by other (non-technology R&D) innovation agencies (e.g. standards development bodies, regulatory bodies), etc.

Quantum technologies exploit quantum physics to achieve functionalities and performance which cannot be obtained from devices based on classical physics. Although many important modern technologies (e.g. lasers, atomic clocks, and microprocessors) already rely on quantum mechanical phenomena, such devices typically process data using classical physics. By contrast, many important emerging quantum technologies exploit quantum mechanical effects to store, manipulate and transmit information. In particular, recent international initiatives related to quantum technology distinguish those which involve the coherent manipulation of quantum mechanical degrees of freedom. Such technologies have the potential to underpin radically disruptive applications, with significant economic and social implications.

The UK has significant strengths in quantum technology research and innovation [UKIPO, 2014; IfM ECD, 2014], not only in key underpinning scientific fields (e.g. quantum optics), but also in emerging application domains, such as quantum secure communications, quantum computation and metrology. The UK government is investing £270 million in these novel quantum technologies [HMT, 2013] with the aim of establishing the UK as a leading actor in quantum technologies-based industries. Investment in this '*Quantum Technologies Programme*' is being delivered by the Engineering and Physical Sciences Research Council (EPSRC) and InnovateUK, in partnership with other key stakeholders, including the Ministry of Defence's Defence Science and Technology Laboratory (Dstl), the National Physical Laboratory (NPL) and the information security arm of GCHQ, the Communications-Electronics Security Group (CESG).

This study is intended to support the EPSRC's quantum technology strategy and programme development, but should also usefully inform the UK *National Quantum Technology Programme*, as well as the activities of other UK R&D agencies with an interest in quantum technologies. This interim report is based on 'desk research' analyses of international QT-related documents which are in the public domain and the English language available from national research & innovation agencies, government ministries and leading research institutes. It also includes consideration of key documents from national academies and learned or professional societies, and a small number of initial interviews have been carried out with QT research experts in different countries.

This initial report focuses on national QT efforts in United States, Germany, and Japan; as well as brief explorations of Australia, Canada, Switzerland and some QT initiatives of the European Commission. The report explores international approaches to QT within the following research domains: quantum computation, quantum communication (including quantum cryptography), quantum metrology (including quantum clocks), and quantum sensors, as well as commenting on related QT-related research and innovation activities in other (sub-)domains.

The following section summarises our main observations regarding international approaches to QT research and innovation. The remainder of the report contains summaries of national QT research activities, strategies and major funding programmes.

1.1. Executive Summary: Key Themes & Observations

1. **International efforts to translate quantum science into practical applications and commercial opportunities**

   All the countries reviewed in this report have significant investments in quantum information science and technology research and innovation. National policy studies and funding programme descriptions all highlight the enormous potential opportunities (as well as the challenges) of exploiting quantum effects to develop disruptive technology platforms underpinning radically enhanced applications in communication, computing and sensing.

   Although many of the international quantum technology (QT) programmes and initiatives identified in this report are still primarily focused 'proof of principle' endeavours in laboratory-based environments, there does appear to be increasing attention and efforts to address technical engineering challenges and application in more 'real-world' environments. There is increasing reference to the involvement of engineers, to the building of 'prototypes', and to the challenges of scaling-up different technology options. There also appears to be attention to the development of enabling tools and technologies for supporting particular quantum technology-related endeavours, with some international strategies and initiatives highlighting the need for particular novel manipulation and detection schemes, or novel measurement and control techniques.

2. **International quantum technology roadmaps and national strategies**

   Despite the acknowledged importance and potential of quantum science and technology, and recent technical advances, there are remarkably few up-to-date published national strategies. Many high profile efforts at roadmapping are now 5-10 years old. For example the most recent publically available '*Quantum Information Science and Technology Roadmaps*' developed for the US intelligence community's *Advanced Research & Development Activity (ARDA)*[1] were produced in 2004[2]. The Japanese National Institute of ICT (NICT) produced its '*Quantum ICT roadmap'* back in 2005. The European '*Quantum Information Processing and Communication Strategic Report*', originally produced for the European Commission in 2005, and has only been updated periodically, although a new version is expected later in 2015. The US *Federal Vision for Quantum Information Science* was published in 2009 and is still the document cited by the most recent US quantum science and technology-related funding calls. In Germany, a substantial report by a *Quantum Technologies* working group, being developed as part of a joint project between the German National Academy of Sciences (Leopoldina), the National Academy of Science and Engineering (acatech) and the Union of German Academies of Science, is due for publication in 2015. It is worth noting that despite the dearth of up-to-date QT-specific roadmaps and strategies, aspects of quantum technology research and innovation are often addressed (and funded) within other governmental technology strategies, for example within national nanotechnology, photonics or ICT strategies [e.g. NRC, 2008; NITRD, 2013; NSET, 2014].

3. **Variations in national Quantum Technology innovation systems**

   There are significant variations between national QT innovation systems, with research and development being funding and carried out by a variety of actors at different levels of technological maturity. Although all the countries considered in this report have strong QT research activities within their university systems, other organisations can also play a major

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[1] The Advanced Research and Development Activity (ARDA) became the Disruptive Technology Office now part of the Intelligence Advanced Research Projects Activity, IARPA.

[2] Although the 2004 ARDA roadmaps continue to be cited, it is likely that there are more up-to-date intelligence studies which are not in public domain.

role. For example, in United States, in addition to the research council-like funding of quantum information science research by the National Science Foundation, there are very significant QT research efforts carried out in the laboratories of Federal mission agencies (i.e. agencies of the Departments of Defense, Energy and national security, etc). Consequently, QT research is focused on developing working technologies which can achieve mission-related goals. In Germany there is significant research carried out in the institutes of the Max Planck, Helmholtz and Leibnitz associations, with strong connections to the broader scientific research base. In Japan, much QT research is carried out by the National Institute for Information & Communications Technology alongside other advanced ICT R&D efforts.

4. National variations in quantum technology research emphasis and focus

Although most of the major research nations considered in this report have activities that span the main quantum science and technology research domains (quantum computing, communication and cryptography, metrology, sensors, etc.), there are some variations in emphasis and scope. These variations seem to have largely evolved naturally, based on pre-existing strengths within centres of excellence in universities and national laboratories. Examples of some distinctive aspects of QT activity in different countries are listed below (and discussed in more detail in the *Country Overview* sections later in this report):

- **United States:** The US has some of the leading university-based quantum science and technology research groups in the world, as well as sophisticated mission-driven quantum technology research carried out by and for agencies of Federal departments, notably the Departments of Energy and Defense, as well as NASA and the *Intelligence Advanced Projects Activity*. Historically, the US has made efforts at interagency coordination through the *Quantum Information Science subcommittee* of the National Science & Technology Council, as well as government studies and convening activities. QT-related research also features within national strategies for nanotech and ICT R&D.
- **Germany:** In addition to some leading university research centres, Germany has significant activity in the institutes of its major research associations, notably the Max Planck Institutes, the Helmholtz and Leibnitz Institutes and, to a lesser extent, Fraunhofer Institutes. Germany has particular strengths in key underpinning scientific fields such as quantum optics. QT has been identified in various versions of the Federal High Tech Strategy, mainly within ICT and nanoelectronics-related themes. Although there is no QT-specific Federal strategy, a substantial study on QT by the German scientific academies exploring the challenges and opportunities for QT science and applications in Germany is currently underway and due for publication in 2015.
- **Japan:** In Japan some of the most significant QT-related research is carried out in national research institutes, notably quantum ICT application research in the National Institute for Information and Communications Technology. The number of major Japanese corporations engaged in QT-related research (e.g. NTT, Toshiba, Hitachi, NEC, Mitsubishi Electric, Fujitsu) is also noteworthy, although much of this is carried out within their own private laboratories.
- **Canada:** Quantum technology research (in particular quantum computing and 'quantum materials') has been highlighted repeatedly within national government science and innovation strategies. Canada has some leading QT research centres, notably at the University of Waterloo, as well as Calgary and Toronto. The high profile QT firm D-Wave is Canadian with significant activities based there as well as collaborations with Canada and US research centres.
- **Australia:** Australia has some eminent quantum science researchers, in particular physics research in quantum optics and quantum gases, as well as silicon-based

platforms for quantum computing and communication. The Australian Research Council is currently funding two major Centres of Excellence related to quantum technologies, which network quantum-related research from around Australia, although these clusters appear to have grown organically from the research base, rather than any strategic efforts by the ARC or Australian government.

- **Switzerland:** The Swiss National Science Foundation has made significant investments in 'Hub'-like *National Centres of Competence in Research* related to QT, with an ambition to build up a domestic network to sustain national excellence in the field. Recent developments of note include ETH Zurich's plans for a '*Quantum Engineering Initiative'* (QEI) with active industry participation, focusing on practical implementation and application of QT. QEI is a joint initiative between ETHZ's Physics and Electrical Engineering Departments in partnership with IBM Zurich.
- **Austria:** Austria has some of the world's most high profile QT researchers, in particular in quantum communications and cryptography. There are several high profile QT centres which are strongly networked internationally, including the Vienna Center for Quantum Science and Technology (VCQ) and activities at the Austrian Institute for Technology which, among other things, coordinates the SECOQC project developing of a 'global network for secure communication based on quantum cryptography'.
- **European Union:** The EU has made significant investment in quantum information science and technology, as well as supporting networking and coordination efforts, including the Quantum Information Processing and Communication 'coordinated action' which developed and updated the EU QIPC strategic report, during the 6th and 7th Framework funding programmes. Quantum Technologies feature in current work programme of the 'Horizon2020' research and innovation funding framework initiative. There have already been relevant targeted funding calls under the auspices of Horizon2020, e.g. for quantum simulation, but other QT topics and themes are also highlighted within other funding areas, e.g. in relation to micro- and nano-electronic ICT technologies, the photonics 'key enabling technology' (KET), disruptive sensing technologies, as well as cybersecurity (and 'trustworthy ICT') research topics.

  An interesting feature of the EU coordination action Qurope is the framework architecture for promoting coordination in the research community provided by what are termed virtual institutes. Lately these virtual institutes, which were originally concerned with fundamental problems, have been complemented with virtual structures in quantum engineering and quantum control, which reflects a motivation to ensure more quantum engineering in the future.

5. International industrial engagement in quantum technology R&D and commercialisation

Several international QT-related strategies or initiative descriptions highlight that bridging the gap between quantum science research and real world QT applications will take time and many iterations of R&D effort. In what appears to be an effort to manage expectations and hype, there is repeated emphasis that many quantum research endeavours are still at pre-application 'proof of principle' stage, while possessing the potential for radically disruptive industrial and economic impact. Moreover, in the earlier stages of QT research, there will likely be multiple solutions along the way to developing the key enabling technologies that will lead to a thriving quantum industry.

Nevertheless, A number of major corporations are engaged in QT-related research, e.g. the Japanese firms NTT, Toshiba, Hitachi, NEC, Mitsubishi Electric, Fujitsu) and major US corporations such as HP and IBM, which have a relatively long record of exploratory QT-related research. Other firms, including the defence-related Honeywell and Northrup Grumann, are also involved. Microsoft recently made a high profile announcement about its ambitious plans for quantum computing research. Much of this corporate research is carried out in conjunction with leading universities and national agencies in QT research around the world.

Many policy-related studies highlight the fact that some commercial QT products, notably Quantum Key Distribution (QKD) systems for secure communications, are already available. And there are emerging commercial activities in other domains, including the high profile quantum computation systems of D-Wave, whose backers and collaborators include NASA, Google, and Lockheed Martin. D-Wave's progress (and the hundreds of millions of dollars of investment it has received) is highlighted in several international policy studies. It is further worth noting that there appears to be evidence of increasing procurement of QT-related R&D by mission agencies in the US (including NIST and DOD, as well as some limited funding through the Small Business Innovation Research programme).

Venture capital is increasingly taking an interest in QT research, an indicator that some tech investors also believe that QT is approaching commercial readiness. In North America, there are funds in the tens of millions of pounds dedicated to funding QT, such as the Quantum Wave Fund and Quantum Valley Investments.

Further information can be found on international commercial activity via this resource, which is supported by the Q-ESSENCE Integrating Project, an FET Proactive initiative originally a part of the EU Seventh Framework Programme. Quantiki is an international project run by a team of volunteers, and is hosted on the servers of the Centre for Quantum Technologies of the National University of Singapore. What this wiki indicates is that devices for cryptography are possibly the most established of the quantum technologies, and that companies are emerging in many parts of the world. The most prominent corporate R&D efforts and high-profile public partnerships tend to be concentrated in traditional leading nations in QT, i.e. US and Japan.

6. International efforts at coordination of interagency quantum technology R&D

To a large degree, national efforts in quantum technologies are somewhat disparate, with limited evidence of concerted efforts at alignment or coordination of collective strengths and resources. A notable exception is the establishment in 2009, by the US National Science and Technology Council, of a *Subcommittee on Quantum Information Science* (SQIS) tasked with developing a vision for Federal Quantum Information Science research. The brief of this multiagency committee was to develop a coordinated approach to Federal QIS research and "*foster research and development, expedite the exploration of the fundamentals of quantum systems and the discovery of potential applications, foster the conditions that will advance the state of the science, ensure an expert workforce and sustain US competiveness in QIS*". Although Quantum Information Science remains a topic of the NSTC, SQIS is no longer listed as an active committee, although its 2009 Federal Vision document is still regularly cited. Other efforts at awareness and alignment include studies by national academies, including the forthcoming German *Quantum Technologies* report, which involved broad stakeholder consultation and engagement, as well as agency-hosted national symposiums and conferences, such as the recent NASA *Future Quantum Technologies* conference and the annual *Quantum Information Technology Symposium* hosted by the Japanese National Institute for Advanced Industrial Science and Technology.

7. International quantum technology definitions and categorisation

Most countries' categorisation of '*quantum technologies*' broadly corresponds to those used in the UK, distinguishing in particular between quantum computation, communication, and sensing. There are, however, variations in emphasis and scope, e.g. quantum metrology, sensing and imaging are often grouped together and, although there are significant R&D efforts related to quantum clocks in a number of countries, they do not feature as prominently as a distinct R&D category as in the UK. '*Quantum simulation*' is sometimes separated more clearly as a distinct category of research and application. Efforts at categorisation often draw distinctions between technologies which exploit quantum effects for functionality but process data using classical physics and those which use quantum mechanical effects to store, manipulate or transmit information. The term 'quantum technologies' is often used to refer to the latter, even though important R&D efforts exploiting quantum effects are also funded under categories such as '*nano-ICT*' or '*Beyond Moore's Law*'. Descriptions of commonly used QT domains are given in Appendix I.

8. Quantum technology networks and national laboratories

It is worth noting that a significant amount of international quantum technology research and innovation effort appears to take place within networks or national laboratories with significant critical mass of researchers and research infrastructure (e.g. US Department of Energy National Laboratories such as LANL, the Japanese National Institute of Information and Communications Technology, NICT and Australian Research Council Centres of Excellence, CQC2T and EQuS, the Institute for Quantum Computing in Waterloo, Canada).

It is beyond the scope of this initial study to explore the added value of such 'critical mass' centres and networks, in terms of opportunities for multidisciplinary collaboration, shared infrastructure, or the ability to address challenges of particular scale and complexity, but there may be useful lessons or effective practices of relevance to the EPSRC Quantum Technology Hubs.

9. Intelligence and Defence Applications of QT (and Implications for Research)

Quantum technologies have significant potential for application in national intelligence and defence contexts. Experts interviewed as part of this study suggested that public domain information about national governments' quantum technology R&D investments (and related strategies and roadmaps) may not reflect all national activities and efforts.

The security and intelligence applications of many emerging quantum technologies mean that some technologies – e.g. cryptographic communications technologies – will be subject to 'export controls' (i.e. government restriction their export, requiring licenses for sellers and excluding certain buyers). Consequently, many countries are endeavouring to establish 'sovereign capabilities' in important new quantum technology domains. These restrictions inevitably present challenges to open and effective multinational research collaboration. Finding appropriate ways of balancing national security concerns with the opportunities of international research collaboration were highlighted by several experts interviewed as part of this study, not least in the context of export control issues inhibiting UK participation in future EU QT initiatives.

2. Country summaries

2.1 United States

The United States has the most diverse and wide ranging level of activity in QT out of any country in the world. There is cutting edge activity being carried out at university, national agency, and private sector level. The multiplicity of agencies includes the National Institute of Standards and Technology (NIST), the National Science Foundation (NSF), the National Aeronautics and Space Administration (NASA), the intelligence agencies, and government departments including the Department of Defense (DOD) and the Department of Energy (DoE). Some of the national laboratories, those associated with the DoE (e.g., Los Alamos, Sandia, Oak Ridge), are important players in QT in the US.

Despite the perceived importance and potential of quantum technologies, there are few up-to-date comprehensive national strategies or roadmaps. For example, the highly cited '*Quantum Information Science and Technology Roadmaps*', developed for the US intelligence community's *Advanced Research & Development Activity* (ARDA)[3] on quantum computation and quantum cryptography, were produced in 2004. These studies identified many different technical facets and challenges associated with emerging quantum technologies. Despite being over 10 years old, these roadmaps continue to be cited, although it is likely that there are more up-to-date intelligence studies which are not in public domain.

The US National Science and Technology Council (NSTC) convened an interagency group called the Subcommittee on Quantum Information Science (SQIS) "to examine and coordinate Federal efforts in quantum information science and related fields". The SQIS 2009 report '*A Federal Vision for Quantum Information Science*' is still the document cited by the most recent US quantum science and technology-related funding calls. While there have been no recent publically available outputs from this committee, there continues to be significant interagency interaction. Although most R&D agencies, however, have their own priorities for quantum technology research and development, and appear to be making their investments and devising their programmes accordingly. Overall, there is a general sense of a transition in QT – as evidenced, for example in NASA's QT conference of 2012, which explored challenges of moving beyond the science and laboratory prototypes to deploying quantum technologies in real mission applications.

Key QT Actors in the US

The National Science Foundation is the main funder of university-based QT research in the US. NSF awards support curiosity-driven and applied research in many branches of quantum technology, through a range of mechanisms from individual PI grants to large research centres. The NSF's 2012 CISE-MPS Interdisciplinary Faculty Program in Quantum Information Science is motivated by the NSTC's 2009 interagency group document, and will be renewed again in 2015. Among other efforts, awards for quantum research are also made to the Division of Mathematics and Physical Sciences via Investigator-Initiated Research Projects and the *Physics at the Information Frontier* programme. And within the Division of Electrical, Communications and Cyber Systems, a programme entitled Electronics, Photonics, and Magnetic Devices funds research related to quantum devices. Some high profile NSF-funded activities include the Institute for Quantum Information and Matter (IQIM) at

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[3] The Advanced Research and Development Activity (ARDA) became the Disruptive Technology Office now part of the Intelligence Advanced Research Projects Activity, IARPA.

Caltech, which carries out research into quantum information science, quantum condensed matter physics, quantum optics, and the quantum mechanics of mechanical systems.

The National Institute of Standards and Technology has a number of quantum related activities that it oversees, spanning almost the entire range of quantum technologies. NIST has had a test bed for demonstrating quantum communications technologies and cryptographic key distribution since 2004. Within NIST itself there is the Quantum Electronics and Photonics Division (whose topic areas include Quantum Information and Measurements), the Quantum Physics Division, and the Quantum Measurement Division (which contains a Quantum Processes and Metrology Group). Its activities further extend to quantum simulation. And since 2001, NIST has been running the ITL Quantum Information Program, which is engaged in quantum computing and quantum communications. NIST is also a partner in an interdisciplinary centre called the Joint Quantum Institute, along with the University of Maryland and the Laboratory for Physical Sciences.

As for NASA, most of their quantum research is conducted in the NASA Ames Research Center, an interdisciplinary centre "bringing together Space scientists, physicists, computer scientists and engineers". This research centre has research groups in metrology, non-linear systems, optics and laser physics, silicon based devices, quantum algorithms, and many body systems and entanglement. NASA also collaborates with the Department of Defense, Princeton University and Lawrence Berkeley National Laboratory in quantum computing projects. Also located in Ames, in the Advanced Supercomputing Facility, is the Quantum Artificial Intelligence Laboratory (QuAIL). This research team investigates quantum computing, and uses a D-Wave Two™ quantum computer to evaluate "quantum computing approaches to help address NASA challenges", with particular emphasis on quantum annealing. In 2012, NASA convened a significant conference on quantum technologies, which gathered leading researchers from around the world to take stock of recent advances in QT and assess their potential impacts. The conference primarily focused on quantum measurement, quantum computing, and quantum cryptography and key distribution.

The Department of Defense (DOD) has interests in quantum technologies. An examination of the 2015 budget estimates for the Defense Advanced Research Projects Agency (DARPA) will in fact reveal considerable and wide ranging investments in quantum related projects, with significant budgets. Furthermore, the Office of the Assistant Secretary of Defense for Research & Engineering oversees a National Security Science and Engineering Faculty Fellows (NSSEFF) programme, and it is perhaps significant that two of the incoming ten fellows in 2014 are experts in quantum science, with quantum information science again cited as a research priority. The DOD also has notable interests in quantum imaging. And the US Army Research Office, an extramural basic research agency, fosters collaborations abroad, for example by helping to fund the Centre for Quantum Computation and Communication Technology in Australia.

The Intelligence Advanced Research Projects Activity (IARPA) conducts research programmes, a significant one being Quantum Computer Science, which examines the "computational resources required to run quantum algorithms on realistic quantum computers". Other relevant projects run by IARPA included the Multi-Qubit Coherent Operations Program and the concluded Coherent Superconducting Qubits programme. It is difficult to ascertain a comprehensive picture of defence and intelligence agency activities. The publicly available information about IARPA's non-classified QT activities includes a sizeable superconducting computing project ("superconducting computing can, and mostly does, impute to quantum computing — though not always") with IBM, Raytheon and Northrop Grumman.

The US Department of Energy funds a lot of research, primarily through the national laboratories with which it is associated. Oak Ridge National Laboratory has a Quantum Information Science (QIS) group in its Computational Sciences and Engineering Division, which investigates quantum computing, communication and sensing. QT are a concern of other Research Areas in Oak Ridge as well, such as Computer Science. At Los Alamos National Laboratory, there is the Quantum Institute, which is largely concerned with quantum cryptography and quantum computing. And at Sandia National Laboratories, there are varied quantum related activities. A Quantum Systems group is focused on quantum information, sensing, and communication. There is also a Computing and Information Science group that explores quantum computing as part of its activities.

The National Academies are comparatively less active in this space. However, the Board on Physics and Astronomy of the National Academies produced a report in 2007 entitled Controlling the Quantum World, and the board has since formed a Committee on Atomic, Molecular, and Optical Sciences to follow up on the agenda laid out in that publication.

Business activity is growing, and notably large corporations are taking an interest in quantum technologies. Microsoft is supporting research into quantum computing in a number of leading universities, while Google is involved in the same collaboration with NASA to support the efforts of Canadian-based company D-Wave. This quantum machine learning research is carried out in the Quantum Artificial Intelligence Laboratory (QuAIL) hosted at NASA's Ames Research Center. In addition to this relationship, Google supports a superconductivity research team in Santa Barbara, a collaboration that is also in the cause of building a quantum computer. Other companies, including IBM (as part of a $3 bn (~ £2 bn) investment), are involved in quantum computing research.

Quantum technologies are attracting more interest from venture capital, with several funds set up with the intention of being dedicated to funding QT. A notable QT-specific venture capital fund in the United States, Quantum Wave Fund, is based in Boston and Moscow and largely run by Russian scientists and investors.

2.2 Germany

In addition to some leading university research centres, there is significant activity in the institutes of Germany's major research associations, notably the Max Planck Institutes, but also the Helmholtz and Leibnitz Institutes and, to a lesser extent, the Fraunhofer Institutes. Germany has particular strengths in key underpinning scientific fields such as quantum optics. QT activity in Germany is not evenly distributed among these various actors. Despite perceived opportunities for practical application and commercialisation there is a comparative lack of activity in the industrially-engaged Fraunhofer Institutes, for example, while some Max Planck Institutes are quite engaged. Nevertheless, experts interviewed as part of this study suggested that quantum technology research in Germany is starting to benefit from relatively high levels of Federal investment in mechanisms that support the transition from applied science into engineered technologies.

While many research interests are pursued, and several high profile initiatives have been supported at a federal level, this has not yet been joined up into a national strategy. The last German high-tech strategy launched by the German Ministry for Education and Research (BMBF), contained a programme on quantum communication within its ICT 2020 agenda. This programme pays particular attention to practical technical challenges, including research into quantum repeaters, which is now in its second stage. Research institutions, universities, and companies are all eligible to apply for funding. The new High-Tech strategy is less explicit in terms of direct references to quantum technologies, but QT research is relevant to many of the application domains and economic and societal challenges highlighted. It appears that, within the new strategy, work will continue on quantum repeaters, with announcements expect on other quantum technology domains. There does not appear to be an overall systematic strategy identifying particular QT R&D priorities within the high tech strategy itself.

One very notable national study related to quantum technologies is being carried out[4] by a working group under the auspices of the Leopoldina, the German National Academy for Sciences, in conjunction with acatech, the German National Academy of Science and Engineering, and the Union of German Academies of Science. The working group is tasked with establishing the "significance of quantum technology for Germany as a location of business and science" and making recommendations for the development of this area of research, and has already convened conferences to discuss this topic.

The prominent research organisations and associations have varying degrees of interest in quantum technologies. Several Max-Planck institutes (MPIs) are involved with quantum research, both in a curiosity-driven sense and in the context of quantum technologies, and some are participants in the aforementioned centres and institutes. MPI for Solid State Research (Stuttgart) is a participant in the IQST, and MPI for Gravitational Physics (Albert Einstein Institute, Hannover) is a partner of QUEST. MPI for the Science of Light (Erlangen) works on quantum sensors and quantum optical communications. MPI for Quantum Optics (Garching) is engaged in a number of quantum related projects, both at a theoretical and experimental level, encompassing quantum optics, computing, and communication.

Concerning the Leibniz Association, there is quantum related activities in several institutes, including Greifswald and Dresden. The Helmholtz Association has a programme on Future Information Technology. Foresight exercises by the Fraunhofer Society indicate interest in quantum information and quantum computing. Meetings have been convened by acatech on nanoelectronics, within which QT feature heavily. The German Research Foundation (DFG) is apparently relatively uninvolved in this space, but among its Collaborative Research Centres there are some quantum activities.

An examination of research activities across German universities will tend to indicate particular strengths in the area of quantum optics. Furthermore, there are some noted research initiatives across the country.

The Center for Integrated Quantum Science and Technology *IQ*ST is a joint initiative of the University of Ulm, the University of Stuttgart, and the Max Planck Institute for Solid State Research (Stuttgart), with a number of other cooperation partners. *IQ*ST is located in the state of Baden-Wurttemberg, and is largely supported both by the local ministry and the two universities (Ulm and Stuttgart). There are several other local universities providing support, along with large companies based in the state, including Bosch. *IQ*ST is a centre that takes an integrated approach, seeking to "systematically foster the synergies between chemistry, electrical engineering, mathematics and physics and thus promote Quantum Science as a whole – from its foundations to its technological applications". Their activities are informed by this vision for the centre, with capabilities being built from the ground up over recent years. IQST's interests in technological applications extend to technology transfer, industrial partnership and the creation of start-ups (with some early successes in biomedical quantum sensing technologies). The five research areas of IQST are: Foundations of Quantum Science, Complex Quantum Systems, Light-Matter Interface, Tailored Quantum States, and Quantum Electrical and Optical Engineering.

Other institutions include the Cluster of Excellence QUEST, the Centre for Quantum Engineering and Space-Time Research, hosted by Leibniz Universität Hannover (LUH) and featuring several other partner institutions. QUEST, which is being funded for 5 years within the Excellence Initiative of the Deutsche Forschungsgemeinschaft (DFG), has four main areas of research (not all of which are

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[4] The QT project is due to end in December 2014 with a final report expected by April/May 2015.

intended to serve future quantum technologies): Quantum Engineering, Quantum Sensors, Space-Time Physics and Enabling Technologies.

Another notable research laboratory is the Karlsruhe Institute of Photonics and Quantum Electronics (IPQ), whose main focus is photonic communications and microwave applications. Its research covers high-speed optical telecommunications, nonlinear optical communications and photonic crystal and nanophotonic device research.

2.3 Japan

Although there is no single national strategy for quantum technologies in Japan, there are significant QT-related research efforts, with extensive academic, government agency, and corporate involvement. There is particular emphasis on QT research related to advanced ICT systems.[5]

Notable among these activities is the Quantum Information Processing project operated out of the National Institute of Informatics and supported by JST, part of the just concluded FIRST Program partly managed and operated by JSPS[6]. Of all recent QT initiatives in Japan, the FIRST project, a programme that ran for four years, is that which had greatest government visibility. The ambitions for the FIRST project were that it would generate new industry, and while the government was ultimately pleased with the publication record, they were disappointed with the lack of patents that accrued. A feature of Japanese research grants is that it is difficult to use these funds to pay students. There is much greater emphasis on purchasing equipment, because it puts something back into companies in Japan, and the FIRST project appears to have been no exception.

The FIRST Program has since been succeeded by the ImPACT Program (Impulsing PAradigm Change through disruptive Technologies). The three major research areas of ImPACT are Quantum Secure Networks, Quantum Simulation, and Quantum Artificial Brain. The early indications appear to be that there is a lot of overlap with FIRST, albeit smaller in scale. The Council for Science and Technology Policy (CSTP) in the Cabinet Office advances key policies toward promoting Japan's S&T policies under the leadership of the Prime Minister. In the creation of the ImPACT Program within that remit, ¥55 billion (~ £310 million) was allocated in the FY2013 supplementary budget.

The National Institute of Information and Communication Technology (NICT) is a key actor in Japanese QT research and innovation, and both conducts research internally and funds outside partners. NICT investigates what it calls "quantum info-communications technology" (Q-ICT), and has created a roadmap for ICT in Japan (almost a decade old). Compared to similar exercises in the US and Europe over the last decade, this roadmap did not extend across all QT domains, being more narrowly focused on quantum communications. As well as optical communications, there are research efforts in quantum cryptography (e.g., several protocols of quantum key distribution), quantum metrology, quantum repeaters, and quantum computing. NICT started a Q-ICT project in 2001, its mission to "provide technological foundations for unconditional security and ultimate capacity". The former entailed development of QKD systems, with funding provided to public and private organisations (corporations, universities, national institutes, etc.) in order to fulfil this objective. The latter objective was distilled to three main goals: a QKD system for metropolitan IP networks within the 50-km range

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[5] Despite this deep involvement in QT, and contrary to the emphasis of some other nations studied in this review, in terms of national security, there are no moves to classify QT research in Japan.

[6] a research funding policy, amounting to ¥100 billion (~ £563 million), part of the 2009 supplemental budget of the Japanese government and intended to gain a leadership position for Japan in the chosen fields, with 30 "core researchers" selected by the Council for Science and Technology Policy (CSTP) in the Cabinet Office

at a minimum key generation rate of 1 Mbps, a QKD system exceeding 100 km range at a key generation rate of 10 kbps or higher, and basic hardware for a quantum repeater.

Latterly, NICT has been central to The Project UQCC (Updating Quantum Cryptography and Communications). This title is an umbrella acronym for a number of activities, including a conference series, and a test bed called the Tokyo QKD network. Activities under this project follow a template of working both through NICT research laboratories and NICT commissioned research teams from both the public and private sectors. The Project UQCC is currently in its third mid-term plan, whose goals are (1) to make practical use cases of a quantum cryptographic network (2) to develop quantum node technologies, and (3) to apply techniques and devices developed in those research activities to new sensing technologies and metrology.

Beyond NICT, there is range of science and technology organisations and agencies which support QT-related research at some level, including the National Institute of Advanced Industrial Science and Technology (AIST), the Japan Science and Technology Agency (JST), Japan Society for the Promotion of Science (JSPS), RIKEN and the Information-technology Promotion Agency (IPA). Many of these agencies have had or are still running quantum-related activities (AIST are less active than one might have expected, though they do convene an annual quantum information technology symposium).

On the topic of the transition from physics to engineering, there is apparently currently little direct effort to commercialise quantum technologies in Japan, and there is also a general paucity of start-up activity. Government agencies/national labs in Japan tend to have more restrictions on the ability to do start-ups. There is a lot of corporate research, however, some of it government funded. Japan is the home of numerous large corporations with major ICT operations, including NEC, Toshiba (whose interests include the Quantum Information Group in Cambridge University), Fujitsu, and Mitsubishi Electric. Mitsubishi Electric and NEC have previously collaborated on testbeds with NICT, notably on the construction and operation of the Tokyo QKD Network. Through this network, they are also collaborators in The Project UQCC, whose partners include Toshiba Research Europe, ID Quantique, the Austrian Institute of Technology, and the University of Vienna. Tough economic conditions have curbed some of this QT corporate research in recent years.

Although the FIRST programme did serve the role of bringing people together, there are few formal mechanisms for networking the QT communities in Japan. Furthermore, with the emphasis on experimental work in the FIRST programme, some theorists were left out to some degree, although there are some funds used to support theoretical work, and there is also a series of conferences. The Asian Quantum Information Science (AQIS) conferences are driven by Japanese academics, and have some government money to fund them.

2.4 Canada

Canada has significant research strengths related to quantum technologies, with proactive support from agencies like the National Research Council and Industry Canada. Quantum technology-related research is highlighted in both the 2009 progress report on the science and technology strategy '*Mobilizing Science and Technology to Canada's Advantage*' and the December 2014 strategy '*Seizing Canada's Moment: Moving Forward in Science, Technology and Innovation 2014*'.

The National Research Council (NRC), an agency of the Government of Canada that reports to Parliament through the Minister of Industry, is a supporter of research that provides new platforms applicable in a wide range of industries. And it is primarily in this context – accelerating development of and validating technologies that offer opportunities for Canadian industry – that it supports quantum technologies. Two ongoing quantum programmes overseen by NRC are the recently launched Quantum Photonic Sensing and Security programme (a collaborative programme between industry, government and universities to “develop the quantum photonics technology platform, while developing and delivering medium-term applications in quantum cyber-security and photonic sensing”, applications intended to serve the energy, environment, defence security and ICT industries; it is a 7 year programme with a budget of $46M CAD), and Quantum cyber security solutions (photonics-based, to provide security for communications, data storage and data processing) for ultra-secure IT data and networks.

Another significant actor in supporting QT programmes is Industry Canada, the Government of Canada's centre of microeconomic policy expertise. It is this agency that publishes the science and technology strategy. The Perimeter Institute for Theoretical Physics in Waterloo, Ontario, a leader in quantum physics, attracted support ($50 million (~ £26.7 million) – Budget 2007) in the cause of advancing that strategy, to “position Canadian researchers at the forefront of quantum computing”. Budget 2009 provided a further $50 million (~ £26.7 million) investment in the Institute for Quantum Computing at the University of Waterloo, with the aim of making Canada a “world leader in the research, development and commercialization of quantum information technologies”. In the updated strategy from December 2014, quantum computing and materials are identified as important components of the country’s ICT and advanced manufacturing research priorities, respectively. Moreover, an additional $15 million (~ £8 million) over three years has been committed to the Institute for Quantum Computing “to advance its strategic plan”.

The Institute for Quantum Computing (IQC), which originated out of a recognition that quantum science is on the cusp of making the transition to real applications, is envisaged by the Canadian government to “create significant economic benefits for Canadians through breakthroughs in knowledge and technology development”. And while benefiting from government largesse, it has enjoyed greater support again from Research in Motion co-founder Mike Lazaridis, who was provided more than $100 (~ £53.4 million) million in funding since its inception in 2002. Research at IQC is “fundamentally interdisciplinary, spanning theory and experiment to pursue every avenue of quantum information science”, and it specifically targets computing, communication, and sensing. Its longer term objective is to realise a full-scale quantum computer. In the meantime, quantum sensors and quantum cryptography systems are much nearer to commercial readiness.

Aside from Waterloo, there are other institutions with significant quantum institutes, most notably the Institute for Quantum Science and Technology in the University of Calgary and the Centre for Quantum Information and Quantum Control in the University of Toronto. The Government has also launched (in 2008) the Canada Excellence Research Chairs (CERC) Program, to support research and innovation to the tune of $10 million (~ £5.3 million) over seven years. Three of these chairs (out of 22) are currently held by researchers in quantum technologies.

Canada is also noteworthy for being the location of one of the most ambitious commercial enterprises to date in quantum technologies. D-Wave is a company based in Burnaby, British Columbia, and it announced “the world's first commercially available quantum computer” in 2011, a system based on “quantum annealing”. While their technology has attracted scepticism from researchers in the field as to whether it currently amounts to true quantum computing, the company has attracted significant financial backing, and its collaborators include NASA, Google, and Lockheed Martin.

And Canada is home to one of the world's most notable venture capital funds for QT. Quantum Valley Investments is a $100 million (~ £53.4 million) investment fund based in Waterloo (another initiative supported by Mike Lazaridis) that aims "to support the commercialisation of breakthrough technologies in quantum information science", and develop a "Quantum Valley" in the Waterloo Region of Canada.

2.5 Switzerland

Swiss universities are among the leaders in quantum science research. Quantum research is well supported by the Swiss National Science Foundation (SNSF), which annually awards approximately CHF 800 million (~ £559 million) to outstanding researchers across all academic disciplines. The SNSF establishes National Centres of Competence in Research (NCCRs) that exist to "promote long-term research networks in areas of strategic importance for Swiss science, the Swiss economy and Swiss society". In addition to federal funding, NCCRs receive funding from higher education institutions and from third parties. Twenty-eight NCCRs have been set up since 2001, two of them focused on quantum technologies, and they are designed to have enduring legacies for Swiss QT research.

NCCR Quantum Photonics (completed) was the first of these focused on quantum research, and was located in EPF Lausanne. It conducted basic research with a view to seeking potential applications in information and communication technology. The project started in 2001, and continued for three phases of 4 years each (the maximum for NCCR projects; projects are reviewed against objectives after each four years) before being discontinued in June 2013. Over that time it received around CHF 90 million (~ £62.9 million) overall, of which roughly half was provided by SNSF funding. During its existence, the NCCR "Quantum Photonics" generated a number of spin-off companies. At its conclusion, it was expected to constitute a "Swiss Photonics" platform to "serve as the first port of call for science, industry, and the public sector for photonics in Switzerland".

Started in 2011, NCCR Quantum Science and Technology (QSIT) is led by ETZ Zurich. The University of Basel is the co-leading house, but there are in fact 34 research groups throughout Switzerland comprising this NCCR. There is a strong emphasis on collaboration across disciplines (and also across academic, public and private sectors) and its goals range from "present and future engineering applications such as quantum cryptography and quantum computation, to the investigation of new paradigms for fundamental physics such as topological states of matter". More specifically, its research focuses are in spectroscopy of single and few quantum systems, entanglement and strong correlation in few and many quantum systems, and hybrid quantum systems. The overall 4 year budget for NCCR QSIT is 55.5 million CHF (~ £38.8 million) (SNSF contribution for 4 years, 17.3 million CHF (~ £12.1 million)).

ETH Zurich is established as a leading centre of QT research. It is home to the Institute for Quantum Electronics (IQE), whose activities include quantum optics, quantum structure engineering, laser physics, ultrafast phenomena and high field physics. IQE not only collaborates in NCCR QSIT, it is the leading house of the NCCR Molecular Ultrafast Science and Technology (MUST) in ultrafast phenomena. There is also a Quantum Information Theory group in ETH Zurich, which is part of QSIT. ETH Zurich is also developing an ambitious Quantum Engineering Initiative with active industry participation. The new activity will focus on the practical implementation and application of quantum technologies and is a joint initiative between ETHZ's Physics and Electrical Engineering Departments in partnership with IBM Zurich.

Switzerland has produced some notably successful companies exploiting quantum technologies. A number have been spun-off from IQE over the years. ID Quantique (IDQ) was founded in 2001 as a university spin-off, and now has several products, covering network encryption, photon counting, and random number generators. It maintains links with academic institutions by participating in Swiss and European R&D programmes, e.g. the SwissQuantum quantum key distribution testbed from 2009-2011. Also, IBM Research - Zurich works on spintronics, with potential quantum information processing applications.

2.6 Australia

Quantum-related research in Australia is recognised as an area of strength for Australian science by the federal government, and there are initiatives supported by the Australian Research Council (ARC). The ARC is a statutory agency within the Australian Government, whose mission is "to deliver policy and programs that advance Australian research and innovation globally and benefit the community". Examining the nature of Australia's QT initiatives, there is less explicit onus on direct economic benefit compared to other countries. Though there is a strategic imperative to these efforts, and there is also a concerted effort to make Australia's universities part of the international network of leading centres of quantum science.

The most significant efforts in QT in Australia are focused on two Centres of Excellence set up by the ARC. Those are the Centre for Quantum Computation and Communication Technology and the Centre of Excellence for Engineered Quantum Systems. Both are equally funded by the ARC to the tune of AUD24.5 million (~ £12.7 million) over 7 years (though there are further sources of funding beyond that). Both centres are at the core of substantial networks and have a significant number of collaborating and partner organisations, encompassing universities and research institutes both in Australia and abroad, and tech corporations. Despite all these well-established collaborative relationships, however, the two centres apparently operate quite independently of each other.

The Centre for Quantum Computation and Communication Technology, named CQC^{2}T, is administered by the University of New South Wales, and is concerned with developing "strategic information technologies" including "a global quantum computing information network", thereby establishing "unprecedented communications security and computing capability for Australia". The ARC Centre of Excellence for Engineered Quantum Systems (EQuS), in the University of Queensland, is focused on producing "novel devices and technologies through the engineering of quantum coherent systems, enabling powerful new applications across a range of fields". Part of this will entail the creation of a design methodology supporting the development of these quantum technologies.

While the ARC produces an annual report summarising research outcomes and return on investment in research, and a strategic plan for the next three years which it updates annually (the current strategic plan alludes to efforts in NSW to build a quantum computer), it is as yet early to say what ambitions exist beyond the current funding commitments that have been made to these centres.

2.7 Austria

Some of the leading figures in quantum science are based in Austria. And commercial opportunities in QT are acknowledged through the activities of the Austrian Institute of Technology. However, while there is apparently plenty of support for individual initiatives, there is no national strategy for QT in Austria.

Foremost among institutions in Austria pursuing quantum science is the Vienna Center for Quantum Science and Technology (VCQ), a joint initiative of the University of Vienna, the Vienna University of Technology, and the Austrian Academy of Sciences. The VCQ straddles pure research and applications, covering "fundamental quantum physics and novel quantum technologies". The University of Vienna is also a member of the SFB "Foundations and Application of Quantum Science" (FoQuS), a consortium of experimental and theoretical research projects in Innsbruck and Vienna. In the University of Innsbruck, the Institute for Theoretical Physics contains the Quantum Optics Theory Group, whose research interests include theoretical quantum optics and atomic physics, quantum information, and the theory of condensed matter systems.

Another institution with a stake in QT is the Austrian Institute of Technology (AIT), which is jointly owned by the Republic of Austria (through the Federal Ministry for Transport, Innovation and Technology, with a share of 50.46%) and the Federation of Austrian Industries (with 49.54% through the VFFI, *Verein zur Förderung von Forschung und Innovation* - "Association to Promote Research and Innovation"). Within AIT's Digital Safety & Security Department is a unit called Optical Quantum Technologies, which develops quantum key distribution systems, with the intent of exploiting commercial potential. AIT also is involved in standardisation initiatives for quantum technologies, at a national and European (ETSI) level. Furthermore, AIT coordinates the SECOQC-Project, the development of a Global Network for Secure Communication based on Quantum Cryptography, which has partners drawn from across Europe. SECOQC intends to "provide the basis for long-range high security communication in a network regime that combines the entirely novel technology of quantum key distribution with solutions from classical computer science, network design and cryptography". The technologies being advanced by this project include producing efficient and stable QKD devices and network-wide key distribution equipment (key-repeaters or node-modules).

Quantum science is also supported by the Austrian Science Fund (FWF), Austria's central funding organization for basic research. The FWF's Research Networking Programmes (RNPs) support programmes established by the European Science Foundation (ESF) over several years, such as Quantum Spin Coherence and Electronics (QSpiCE). Below the national level, there is the Vienna Science and Technology Fund (WWTF) to promote science and research in Vienna, which obtains its funds from a private foundation in the private sector. This fund has supported several quantum related projects, on topics such as optomechanical systems for quantum information processing, quantum networks, and high performance algorithms for quantum key distribution.

2.8 European Union

The European Union views QT as an important priority for Europe. The avenues by which cutting edge science is advanced in Europe are largely contained within Europe 2020, the EU's growth strategy for the coming decade. The Innovation Union is one of the seven flagship initiatives of the Europe 2020 strategy for smart, sustainable and inclusive growth. And Horizon 2020, a financial instrument implementing the Innovation Union, is the biggest EU Research and Innovation programme ever with nearly €80 billion (~ £58.5 billion) of funding available over 7 years up to 2020. Once research topics reach a level of sufficient maturity, research is transferred to the Societal Challenges sections of Horizon 2020, which will involve piloting, demonstration, and test-bed activities. Quantum related projects are also funded by the European Research Council.

Quantum Technologies feature in different research areas of the 'Horizon2020' work programme. There have already been relevant targeted funding calls under the auspices of Horizon2020, e.g., for quantum simulation, but other QT topics and themes are also highlighted within other funding areas, e.g., in relation to micro- and nano-electronic ICT technologies, the photonics ‘key enabling technology’ (KET), disruptive sensing technologies, as well as cybersecurity (and ‘trustworthy ICT’) research topics.

This theme of bridging from the science to the engineering of concrete QT is a common refrain in European level initiatives. The whole gamut of quantum technologies is considered of interest to the EU, from quantum computing to communication, security, metrology, sensing, simulation and material science. QT feature in current and upcoming funding calls, generally within ICT related topics, such as the funding call ICT 2015 (total budget €561 million (~ £410 million)), whose topic is generic micro- and nano-electronic technologies. Projects here may include activities “related to modelling and simulation: e.g., quantum and atomic scale effects” and the study of “new computing paradigms like quantum computing”. The objective of this funding call is to ensure “Europe's global position in the area and to ensure strategic electronic design and manufacturing capability in Europe avoiding dependencies from other regions”. Part of the scope will involve “new computing paradigms like quantum computing and neuromorphic computing with a focus on their future integration with Si technologies”. Moreover, other work programmes such as photonics (quantum optics) and cybersecurity (quantum key distribution systems and networks) will include quantum R&D. In addition, in ICT 26 - 2014: Photonics KET, new device concepts “based on quantum optics or quantum technologies” are mentioned in the context of disruptive sensing technologies, and in ICT 32-2014: Cybersecurity, Trustworthy ICT, post-quantum key distribution and several aspects of QKD appear.

A prior call, FETPROACT 2014, with a budget of €35 million, is concerned with quantum simulation, and is viewed as complementary to the quantum technology research topics that are called under the ICT part of the LEIT (Leadership in Enabling and Industrial Technologies) Work Programme 2014-15. The expected impacts of all these activities are the “build-up of core competences for the wider exploitation of quantum science and technologies in mainstream engineering”. The QT related aspect of the FET Proactive programme is currently known as the FET Proactive Initiative: Quantum Information Communication and Technologies (QICT), whose objective is to “conceive theoretically and develop experimentally novel and powerful technological applications of quantum coherence and entanglement”.

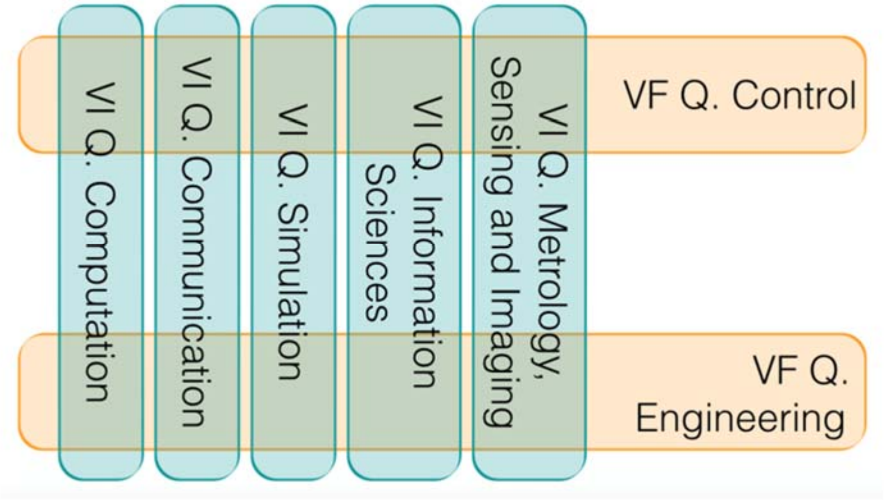
There is currently a coordination action is called Qurope – coordination actions are one of the funding schemes by which FP7 is implemented, and cover the “coordination and networking of projects, programmes and policies” – whose committee, featuring many of the leading investigators in the field, produced a Quantum Information Processing and Communication (QIPC) roadmap in 2013; the next one is due for late 2015. The goal of the accompanying positioning document is to promote QIPC research in Europe and give direction to future European Commission initiatives. It notes that funding for quantum information technology has risen elsewhere in the world, and calls for the necessary infrastructure, funding, and coordination at European level that is required for Europe to remain competitive in a field in whose early development Europe has been prominent. Roadmapping for metrology has also recently been carried out by EURAMET, the European Association of National Metrology Institutes.

Within Qurope there are five “virtual institutes”, which serve as a framework architecture for “interaction and coordination with the scientific branches of the research community”. Those five Virtual Institutes (VIs) are in: Quantum Communication, Quantum Computation, Quantum Information Sciences, Quantum Simulation and Metrology, Sensing and Imaging. Each Virtual Institute “unites some prominent experts in the corresponding field, providing a contact point for consultation and feedback in the relevant areas”. Moves are underway to ensure more quantum engineering in the future, and as such the structures are due for overhauling, with intentions to bring in more researchers from materials and device engineering, quantum control engineering, etc. To that end, two new structures called virtual facilities for **Quantum Engineering** and **Quantum Control** are being created.

It is envisaged these new structures, reflecting the “evolution of the field from the conception of the original VIs”, will:

(1) Reflect the current status of the Quantum Technologies community;
(2) Raise the visibility of the identified new fields in the physics and related communities, funding agencies and industry partners;
(3) Develop a shared vision harmonised with all the existing VIs;
(4) Coordinate the European efforts in the identified field.

A new structure incorporating these virtual facilities, both of which touch upon each of the existing Vis, is visualised thus in the following table.



- **Quantum Control.**
  Practitioners are agreed that quantum optimal control is essential for the design of quantum technologies, which are based on interference and entanglement. Not only is it vital to enable the necessary precision given the sensitivity, power, timing and accuracy of instruments, there is also the interaction with the environment, which can destroy the quantum resources of interference and entanglement. In computation, metrology, sensing and simulation, quantum control will assist hardware to perform optimally, given its imperfections, and it is also considered important for quantum communication and information security.

- **Quantum Engineering.**
  Key quantum engineering challenges range from the demonstration of fault-tolerance and logical qubit operations to the realization of multi-node quantum networks. Typical engineering challenges such as manufacturability, reliability and affordability will all need to be addressed for QT to demonstrate its viability. There remain open questions such as the optimal qubit representation and realization of a quantum repeater, and also the challenge of incorporating and integrating large numbers of quantum bits with classical electronics. Not only are there new challenges in quantum computer architecture, integrated quantum-classical circuit design, and high-yield qubit fabrication arising therefrom, there are also issues raised in Quantum Information theory, such as practical quantum compilers, languages and protocols for testing algorithms and simulations. Engineering challenges have also been identified in quantum communication, metrology and sensing. Some of these engineering problems are already being regarded as urgent, hence moves to incorporate them into VIs at this stage.

Another coordinated action, entitled "Optimal Control of Quantum Systems" (QUAINT,) has already initiated a virtual structure on Quantum Optimal Control. This has been done "as a means to promote the quantum control perspective and disseminate quantum control techniques to the broader quantum physics community".

Finally, things are moving forward towards commercialisation in Europe, though there is a variation in timelines according to the maturity of the various quantum technologies. High level events under the aegis of the European Commission are already examining this question of the transition from quantum science to quantum technologies. Quantum computing is regarded as the most long term development challenge, and as such is the furthest out along that timeline. The greater focus, therefore, is on fields closer to maturity, e.g., sensing.

2.9 Other Countries

Detailed exploration of the QT strategies and research initiatives of other countries are beyond scope of this study and interim report. Nevertheless, it is clear from our analysis of international studies and policy reports that there are notable activities and important developments in several other countries, including:

Singapore
Established in 2007, the Centre for Quantum Technology (CQT), an autonomous research centre hosted by the National University of Singapore, is a very prominent global centre for QT. The founding Director of CQT is Artur Ekert, also Professor of Quantum Physics at the Oxford University's Mathematical Institute. CQT's operations are supported by its stakeholders through direct funding and other contributions. CQT received $36.9 million (~ £18.1 million) from the National Research Foundation (NRF) of Singapore to fund core operations in 2014, which follows the $158 million founding grant awarded by NRF and the Singapore Ministry of Education in 2007 to establish the centre. CQT also has a strong portfolio of competitive QT research grants.

China
China's QT interests are largely in the area of quantum communication. In 2014, China began installing the world's longest quantum-communications network (including a 2000km link between Beijing and Shanghai) and has announced plans to launch a 'Quantum Science Satellite' in 2016 to exploit space-based QT cryptography. China's engagement with QT is growing, as can be gauged from the fact that China patented five times more than the EU in QT between 2009 and 2012. In November 2014, China hosted the *International Conference on Quantum Communication, Measurement and Computing* (QCMC) for the first time, an event that paid significant attention to "industrialization in the quantum information field".
The profile of QT research interest in China is demonstrable, with the Chinese Academy of Sciences having one of the largest institutional outputs of QT publications in the world. Perhaps most notably among Chinese researchers, Prof. Pan Jian-Wei at the University of Science and Technology of China (USTC) has recently had high profile articles published in Nature and Nature Photonics – work that has also been discussed in Physics World. And companies are also emerging from this academic research in China. USTC is a cofounder of QuantumCTek, a group of companies that work on quantum communication systems, providing multi-protocol network security products and services based on quantum technology.

The '*Bulletin of the Chinese Academy of Sciences*' published in November 2014 highlighted some major science & technology breakthroughs to be expected in China in the coming decade. In particular, that issue of BCAS included a section on '*Major Breakthroughs Expected in Quantum Communication*'. Referring to a "roadmap for wide-area quantum communication technologies", important potential breakthroughs in China include:

- Advances in the performance of key **fibre-optic quantum communication devices** – in particular, improvements are anticipated for single photon detectors (in terms of higher operating frequencies, low dark count rate and high detection efficiencies),

- Advances in (cold atom-based) **quantum repeaters** with significant improvements anticipated in quantum storage lifetimes

- Progress in a range of **satellite-related quantum technologies**, including: satellite-to-ground free space quantum communication, inter-satellite quantum communication, all-weather free-space quantum communication, etc.

- There has been a range of other ambitious initiatives in China, such as 2012 trial of a "quantum banking information verification network" in the city of Hefei. Developed by the University of Science & Technology of China and the Xinhua News Agency, the piloting of a city wide quantum communication network was claimed to be the world's first.

Russia

Investment in Skolkovo, the innovation centre situated near Moscow, is a high-level priority for the Russian Government. The Russian Quantum Centre (RQC) in Skolkovo has received funding of 1.33 billion rubles (~ £15.5 million) from the Skolkovo Foundation, and it also has links with the Quantum Wave Fund, from whom it has also received investment.

The Netherlands

The view of QT activity in the Netherlands is largely centred on quantum computing. TU Delft is a prominent centre for research into superconductor- and semiconductor-based qubits. A recent large-scale initiative is the launch of the QuTech Centre – a partnership between TU Delft, TNO (Netherlands Organisation for Applied Scientific Research) and industry partners. The founding of the centre is based on a conviction that "quantum science has entered a transformational phase from university-based research to engineering-driven technologies" – in 2014, QuTech was declared by the government to be one of four 'national icons' which will have major social and economic impact, contributing to future prosperity and dealing with global social challenges. QT startups and SMEs are already emerging to become part of the European high-tech industry, with the intention of gaining a share of the future quantum sector.

It has recently been announced that €135m will be invested in the "development of a super fast quantum computer", a partnership involving the "Dutch government, TNO and other organisations". The investment will be centred on QuTech, and will be spread over a ten-year period. Microsoft has already been investing in the institute since 2010. Over the course of this new round of investment, QuTech will be able to double its research team to 200.

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Appendix 1:
Quantum Technologies: Definitions and Scope

Research into quantum technologies, at a practical and theoretical level, is carried out by a diverse range of actors. It is supported by national governments, through universities and military funding, and also by private enterprise. Brief summaries of some of the key research domains are provided below.

Quantum Computing (QC)

Conventional computers encode data in binary digits (bits), which are always in one of two definite states (0 or 1). Quantum computers use quantum bits (qubits – two state quantum mechanical systems, such as the polarisation of a single photon), which can be a 1 or a 0 or a superposition of both states at the same time. The property of quantum superposition, along with the quantum effects of entanglement and quantum tunnelling, enable quantum computers to perform many different calculations in parallel. A system with N qubits can perform 2^N calculations at once. Quantum computing offers a new kind of computing based on new computing algorithms (e.g., Shor's Algorithm, Simon's Algorithm, etc.).

Quantum computers are built by connecting simple quantum logic gates (analogous to classical gates, these are computing devices that perform one elementary quantum operation, usually on two qubits) and building them up into quantum networks. As of 2014, quantum computation has been achieved using a small number of qubits. Key technical challenges for building quantum computers include overcoming the problem of decoherence (losing quantum information to the outside environment) as the number of quantum gates in a network increases, and the finite lifetime of information stored in qubits, which steadily decays.

Quantum communication

Quantum communication refers to the process of transferring a quantum state (which code quantum information, called qubits) from one place to another, traditionally between a sender named 'Alice' and a receiver named 'Bob'. There are two ways of accomplishing this task. One is analogous to classical communication and involves sending a quantum bit over a quantum communication channel. The other way has no classical analogue, where a quantum bit is transferred without utilising a quantum channel. Instead, a classical communication channel is used along with a pair of entangled states, with quantum operations applied locally.

The best known example of quantum communication is Quantum Key Distribution (QKD). This enables the distribution of a sequence of random bits whose randomness and secrecy are guaranteed by the laws of quantum physics. These sequences can then be used as secret keys with conventional cryptography techniques to ensure the confidentiality of data transmissions.

Quantum repeaters are necessary for the distribution of quantum states over long distances.

Quantum cryptography

The most important problem in cryptography is the key distribution problem. In classical cryptography an absolute security of information cannot be guaranteed. Quantum cryptography relies on the laws of quantum mechanics, where the Heisenberg Uncertainty Principle and quantum entanglement are of particular relevance.

Quantum cryptography enables two parties to exchange an enciphering key securely over a private channel such that eavesdroppers are denied access. There are two different types of quantum cryptographic protocol. One uses polarisation of photons to encode bits of information, the second uses entangled photon states to encode the bits. Information is protected by the laws of physics.

Attempting to obtain information about quantum data disturbs that data, which makes eavesdropping detectable.

Quantum Metrology

Quantum metrology utilises quantum effects to set the standards that define units of measurement – quantum mechanics sets the ultimate limit on the accuracy of any measurement. Therefore quantum metrology offers the promise of measurement techniques that enhance precision and sensitivity beyond that possible in a classical framework.

Quantum Sensors

Quantum systems can be employed as high-performing sensing devices, with sensitivities and resolutions that are superior to classical systems can be achieved using quantum sensors. Quantum phenomena, such as quantum entanglement, can be exploited for the purposes of imaging, spectroscopy, navigation, magnetic field sensing, etc.

Quantum Optics

Quantum optics refers to a domain of research that deals with the application of quantum mechanics to phenomena involving light and its interactions with matter. Those applications include metrology, sensing, communications, and computing. It is a field that is continuously advancing, owing to new photon sources, new photo-detectors, and better optical fibres.

Quantum imaging is a sub-field of quantum optics that also exploits quantum entanglement, spatial squeezing of light, and the near-field/far-field duality. Quantum imaging demonstrates some peculiar features, including enhancing the spatial resolution of imaging beyond the diffraction limit. Further examples of quantum imaging are quantum ghost imaging, a technique that produces an image of an object by combining information from two light detectors.

Quantum Simulation

Simulating quantum mechanics is a difficult computational problem, especially for large systems. Quantum simulation involves using controllable quantum systems to investigate the behaviour and properties of other, less accessible ones. Quantum systems such as neutral atoms, ions, polar molecules, electrons in semiconductors, superconducting circuits, nuclear spins and photons have all been proposed as quantum simulators.

Quantum simulation offers the potential to simulate complex many-body systems of a kind that are too demanding for classical computers, with potential applications in condensed-matter physics, high-energy physics, atomic physics, cosmology, etc.