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The Emerging Quantum Technology Industry: capital cities, entrepreneurship, and policy

by

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Abstract

This paper provides an empirical account of the evolution of the key emerging technology, quantum technology. It presents a survey of academic and industry sources to explore the current position of Washington DC and London UK as concentrations of relevant innovation activity. It explores the conditions under which certain parts of the innovation process are located in these two capital cities. Elements of the innovation process include the presence of start-up businesses and the emergence of quantum industry clusters in these two places. Also of note is the gender dimension in the commercialisation process, specifically the under-representation of female entrepreneurs and senior decision-makers.

1. Introduction

Quantum technology is, like nuclear fusion, a technology that is taking a long time to come to commercial fruition. Current hardware is not big enough in scale nor stable enough to fulfil the promises that are made for it. However, some aspects of how to exploit quantum technology when it exist, such as algorithm development, are beginning to be commercialized -- moving from laboratory experiment into commercial solutions and deployments that work on existing (usually simulation) hardware.

Quantum technology has enormous promise: in 2016 it was reported that, ‘If today AI and 5G are seen as the technologies that will enhance the competitive capability of companies and countries, quantum will start doing that during the next 10 years. Quantum will dramatically change different economic sectors in the next decade’ (UK Government Office of Science, 2016). Over several decades governments-- and more recently large organisations, notably IBM, Google, Microsoft, Intel and more recently Amazon-- have invested significant sums. In the UK, UKRI announced the investment of £93M through EPSRC and STFC in a centre in Oxfordshire as part of a £1B programme started in 2013[1]. Most but not all of the current UK work is on application development and consultancy, rather than on building hardware solutions.

While there is caution about *when* quantum technology will deliver its promises, it is now timely to explore where it is being developed and why that geography matters. It has been long established that innovative efforts are not evenly and randomly distributed among all possible technological areas and tend to be relatively concentrated in specific technological fields (Evangelista et al. 2019), in particular countries, and within them – in specific places. Quantum technology is past the early stage of development from a theoretical research-based activity to commercial application with a growing industrial base (Sussman et al. 2019).

[1] https://physicsworld.com/a/quantum-technology-why-the-future-is-already-on-its-way/

As with previous crest- of-the-wave technologies in computing, the problem in certain industries is that major players cannot afford to become left behind. Thus for example encryption leaders will be content if no-one has a new technology; or if they have the same technology or better than do others, but not if others do and they do not. This applies to countries as well as companies: if China or Russia had exclusive access then the West could potentially suffer greatly. Organisations and countries must also be in a position to be able to deploy such a technology quickly if it come to fruition – by having available relevant applications software and human resources etc. This may be easier in a command economy.

Quantum is thus a potential key emerging technology that has to be tracked regardless. In the light of the downside risks, this is especially true for governments. It has been only lightly examined in the academic literature in social sciences. Thus, in this paper we examine the contours of the emergence of this industry. The contours we explore are: its history, the industry's categories as they appear now, the emergence of industry clusters especially around the capital cities of London and Washington, start-up entrepreneurship, and finally -- the role of Government. We ask whether these capital cities and centres of government are primary locations for quantum entrepreneurship, going forward. National governments have recognised the economic potential for this emerging technology, its criticality for national security, and what levers they have for pushing it forward. This includes areas of leverage such as universities, defence agencies, and specialist research bodies, such as energy.

This paper is primarily a survey paper using academic and industry sources. We augmented our sources with some industry analysis especially around quantum start-ups. The evidence suggests that although capital cities can play a pivotal role in the emergence and entrepreneurial stages in technological advance in this key emerging technology, this is not a story of capital cities centrality in inception, discovery and development stages. The paper is therefore concerned with the conditions under which certain parts of the innovation process round quantum technology are located in these two capital cities and what that suggests for its emerging geography of innovation. The paper also has a separate gender dimension-- highlighting the dominance of males in this innovation process.

After the literature review and methodology, we provide an historical overview of the quantum industry. This provides the context to the study. This is followed by a review of the evidence and in the final section we draw some conclusions.

2. Historical and geographical contexts

Quantum technology has been posited as a route to very rapid computing since the 1980s. Theoretically, using sufficiently many reliable quantum gates allows massive parallelism in algorithms and leads to a potential revolution in what is achievable in a given time, for instance making much existing encryption techniques readily decryptable. There are a number of problem areas to be solved and these have changed little over time[2]. These are: being able to set up an initial state reliably, the rate of random hardware errors and their detection and correction, decoherence and the ability to have gates that are faster than the decoherence time to avoid breakdown,

[2] https://blogs.scientificamerican.com/observations/the-problem-with-quantum-computers/

and the need for very low temperatures. Some progress has and is being made in all these areas, especially the temperature one. Thus it is too soon to say when or whether reliable quantum computing will be available. But that fact itself is of concern to governments and large organisations in a number of industries. Funding can thus be viewed as a combination of entrepreneurship encouragement and insurance against being left behind.

Quantum is thus an emerging technology. It is one that is, as yet, barely commercialized. As a starting point, we analyse this technology with lessons from studies of other key emerging technologies (KETs) e.g. electronics (Assimakopoulos et al., 2016), cryogenics (Lawton Smith, 1991; Evangelista et al., 2018). KETs are defined as “Emerging technologies are defined by five attributes: radical novelty, fast growth, coherence, prominent impact, and uncertainty and ambiguity” (Rotolo et al., 2015). Quantum clearly satisfies all of these: concerns over growth by the removal of some central funding has been compensated by the involvement of big players. These highly innovative technologies are knowledge and capital intensive, strongly linked with the intensity of R&D, swift and integrated innovation cycles, requiring high skill employment. Knowledge flows bring together complementary expertise and resources, and promote the cooperation (or/and competition) among companies, academic institutions and public authorities (Cova et al., 2010; Robinson et al., 2013). However, the role of expectations in how the emerging technology will develop and what it will deliver not just in economic terms but also societal implications and public good form part of the evolutionary process (Roberson, 2021).

The geographical focus of this paper is the role of two powerful capital cities, seats of government - London and Washington - in the dynamics of the development of collective technological knowledge. The geographical baton of quantum technology has been carried out initially in universities across two continents: Europe and North America since the 1980s. The role of government is necessarily has to be part of the explanation of where technological advance takes place at particular stages in the innovation process. Each country’s national innovation system (NIS) (Nelson, 1993; Freeman, 1995) comprises a patchwork of research funding agencies ranging from the purely state to hybrid to private not-for-profit institutions – all which have their own agenda. Of course, governments are major actors in NIS. They support R&D because there are ‘spillover’ effects from innovation, meaning that the gains (or lack of losses) to society can far outweigh the benefits to individual innovators. Providing direct R&D funding via grants, loans and subsidies; encouraging collaboration and networking; funding universities.

For example, a major stimulus in the quantum area was US government action in the 1990s which helped to drive developments and provide opportunities for a wider geographical spread of adoption and diffusion. However, it was not until 2013-2014 that Washington and London became leading locations as the focus shifted to applications with well connected consultancy having a significant share.

2.1 Context: The Quantum Industry’s Historical Eras

We present a styled historical timeline of the quantum industry with three stages: Conception (through mid 1990s), Emergence (through 2016), and current stage (2019 onwards), which we label Entrepreneurial stage. The timeline serves to illustrate the history of quantum technology, as well as the points at which the state steps in and how the geography of advance changes.

1. **Conception Stage** (1980s through mid 1990s). Mostly theoretical work based in universities and research labs.
2. **Emergence Stage** (through 2016). University work is still central, but large tech firms play an increasing role, with much government support.
3. **Entrepreneurial Stage** (current). Start-ups financed in part through venture capital emerge and large organisations invest internally.

Figure 1: The three historical stages of the quantum industry
Source: Authors' interpretation

Conception Stage: Pure Research

The conception stage of quantum computing began during the 1980s, first in Russia, initially by a Russian born mathematician Yuri Manin. Manin worked around the idea of realizing computing simulations of quantum systems. It provides a good basis for developing applications. The next step was that the US physicist Richard Feynman based in New York. Feynman won the Nobel prize for physics for his joint work on quantum electrodynamics. In response to Manin's approach he said "Nature is quantum, goddamn it! So if we want to simulate it, we need a quantum computer." [3] His objective was to build a quantum computer and to simulate a quantum computer on it. Feynman's work was then continued in the UK at the hands of David Deutsch, at University of Oxford, who described a general-purpose quantum computer for the first time (Dyakonov, 2019).

While pioneering work was being led in the UK, Peter Shor, at Bell Labs (a private sector research laboratory), USA in 1994, proposed, in a seminal article, an ideal quantum computer able to factor very large numbers much faster than a conventional computer (Vasconcelos, 2020) His algorithm for factorising a number of size N uses O((logN)**3) time and O((logN) space. Similar theoretical algorithms continue to be developed in many other areas including elliptic curve based decryption, sensors, optimisation and networking. All show substantial drops in algorithmic complexity.[4]

Emergence Stage – mid 1990s through 2016

Up until this point the embryonic theoretical visions essentially came out of universities. Next, the boost came from government. The first call for funding proposals in quantum information processing was launched in 1996 through a collaboration of the US Government, the Army Research Laboratory and the National Security Agency (Raymer and Monroe, 2019). The funding participants make clear the priorities.

[3] https://www.technologyreview.com/s/610250/hello-quantum-world/
[4] https://research.aimultiple.com/quantum-computing-applications/

The emergence phase remained largely university-led with a strong research base in the US, UK, Europe and Japan. The decade 2000-2010 is characterised by an increasing effort in research, largely based on university efforts. Academic-led research centres were established during this time: the Institute of Quantum Computing at Waterloo University in Canada in 2002 and the Institute for Quantum Optics and Quantum Information at Innsbruck and Vienna (2003). The first quantum network, the DARPA Quantum Network, among 10 nodes located across Boston and Cambridge, Massachusetts, became operational in the period 2002-2007.

In research terms, the increasing number of papers published per year is a sign of a growth in interest by the academic and research community. This could in part be essentially a response to government funding opportunities with academia “following the ball”. Inevitably the work is largely application oriented deriving algorithms and software. Figure 1 shows that increase, with Peter Shor’s work accelerating output from near zero to 250 papers by 2001.

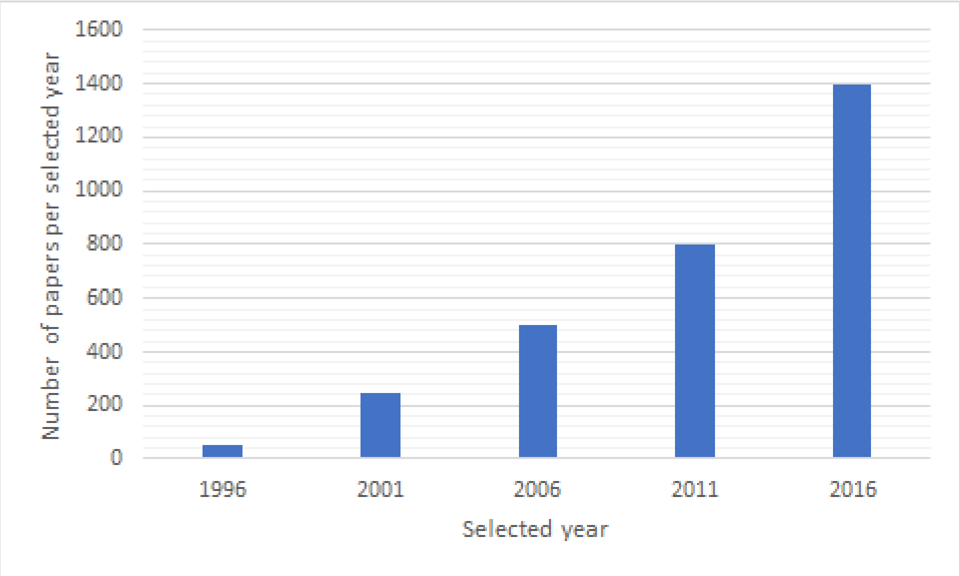

Figure 2: Number of papers published per year in quantum technologies. Source: Elaboration on data from Dyakonov (2019).

Towards the end of this period we begin to see the balanced four-sided innovation engine that emerges in quantum:

- Government
- Commercial – large firms
- Commercial – start-ups
- University

Entrepreneurial stage -- from 2016

By 2019, more players were appearing round the world. This includes government initiatives and deployments such as:

- China is investing in all areas, including a national Q-backbone (Beijing-Shanghai), a Q-satellite, and intercontinental connection (Vienna-Beijing).

- The EU QT-Flagship programme is planning to invest €1bn in 20 projects during the period 2018-2021.
- The Russian Digital Program includes three research centres: Moscow, St. Petersburg and Kazan; several quantum networks testbeds and work towards a Q-satellite launch in 2023.
- The Q-Leap Flagship programme in Japan works in all areas.
- The European CERN has launched IDEASQUARE, a program that brings together researchers and companies on quantum ICT.
- In December 2018, the USA launched the National Quantum Initiative for investing on Q-related activities US$1.2bn in the next five years.
- The UK launched its quantum program in 2014 investing at the time £270 million since expanded to £1Bn over 10 years.

The population of quantum technology companies was growing. Large technology companies were investing in quantum, while quantum start-ups were also growing in numbers (Gibney, 2019). Figure 2 provides a picture of quantum companies in 2019.

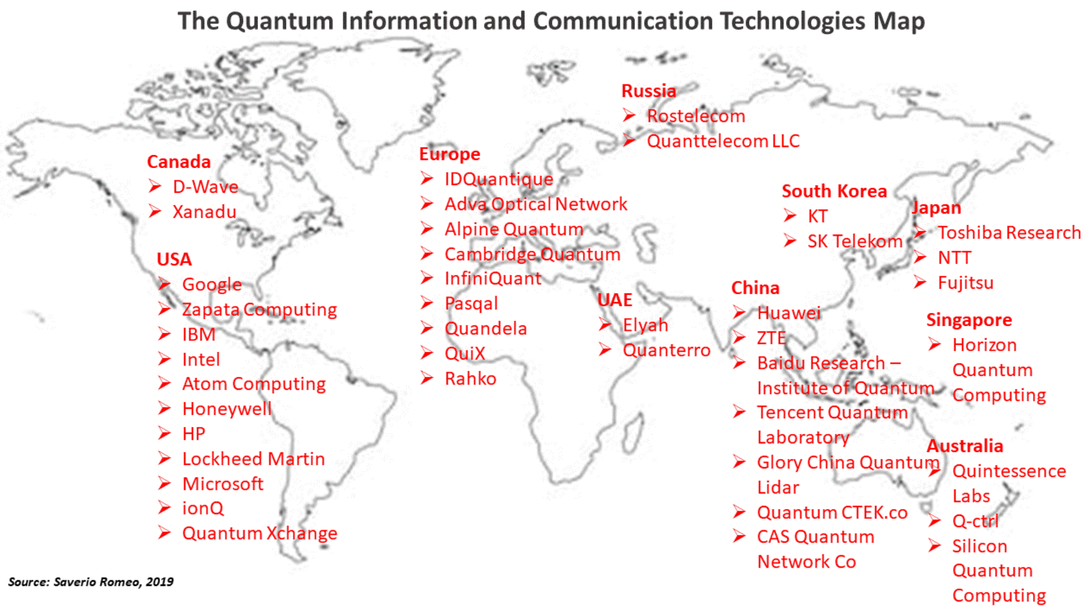

Figure 2. Quantum companies. 2019. Source: Authors' survey

3. Research Methodology

Against this historical background, we are exploring the contours of this industry via secondary sources and some primary analysis of the industry. We have built a Quantum technology company database that now has 75 firms, 27 located in the UK and 48 located in the USA. The data are derived from an existing collection of world-wide quantum companies based on web-search, quantum conference search, information from universities' technology transfer offices and sources such as Crunchbase and Amadeus. Using our data we were able to make insights about firm formation, growth, and capital raised. We also use it to highlight the key industry players. A list of the 75 firms appears in Appendix A.

Categorization of quantum businesses

The business activities of the first wave of quantum companies fall mostly into 5 areas of Box 1.

1) **Sensors and metrology**. Developing sensors using quantum technology to increase accuracy and precision.
2) **Secure communications**. Developing quantum-based security solutions for communication systems.
3) **Imaging.** Developing imaging systems that could perform tasks not possible at the moment, such as 3D imaging and looking behind corners.
4) **Computing**. Developing quantum computers, including computing for solving complex problems and cybersecurity.
5) **Consultancy.** Companies gathering various expertise in quantum technology to advise potential adopters of quantum-based solutions.

Box 1: The quantum technologies industry categories
Source: Authors' analysis

4. Findings

This section provides an analysis of data on start-ups in the USA and the UK. We trace their activities, their growth, government investment and the evolving quantum technology start-up landscape in these locations – and globally. The purpose is to position Washington and London within this landscape. Note that actual manufacture is now largely hidden within existing large technology companies and government organisations so start-ups almost exclusively deal in consultancy or applications/ software development.

4.1 Startups

Our data show that the majority of the start-ups in the USA and the UK are focussed on three quantum segments: computing, secure communication and consultancy (categories 2,4,5 above). This could be driven by governmental priorities as it is here that countries are most at risk.

Our interest is particularly in start-ups, so we devote more attention to that part of the engine. Governments are involved in supporting new firms by, for example, supporting the growth of pools of venture capital and through various tax measures to de-risk start-ups, as well as through direct funding via initiatives and centres.

While the initial stages were university-based, technology companies began to be involved, beginning in the 1990s. Large tech companies, such as IBM (USA) and Japan's NEC began quantum research efforts. And innovation geography shifted to the U.S. West Coast: the IBM's Almaden Research Centre worked with Stanford University on developing systems able to perform Shor's algorithm. Microsoft launched Station Q within its Microsoft Research Station Q, located on the campus of the University of California, Santa Barbara, Quantum start-ups slowly began to appear. In 1999, D-Wave Systems was incorporated in Canada, a pioneering company in quantum computing[5]. D-Wave had various achievements such as the demonstration of a 28 qubit computer in 2007 and 128 qubit computer chip in 2009. More firms appeared after 2010: 1Qbit in Canada (2012), Rigetti Computing in the USA (2013), and Cambridge Quantum Computing in the UK (2014). Another early start up was Swiss ID-Quantique established in 2001.

In 2013, Google launched the Quantum AI Lab (QuAIL) in California. Later QuAIL become a joint venture between NASA, Google Research and the Universities Space Research Association. Private-led research initiatives were happening all over the world: Fujitsu and Hitachi in Japan, Airbus and Carl Zeiss in Europe; Alibaba and Huawei in China. This wide interest from large technology enterprises also drove the attention of governments on the matter, culminating in initiatives such as the National Quantum Technology Programme in the UK announced in 2013 (Knight and Walmsely, 2019) and later, in 2019, the EU Quantum Manifesto (De Touzalin et.al.2016).

We set the inflection point of accelerated activity at 2016. From a policy point of view, 2016 is a turning point in terms of investment in both USA and UK--particularly the UK. That investment has had the direct effect of encouraging and promoting start-up formation, but also the indirect effect to encourage private investments to engage more with quantum. Exhibit 2 shows how the sector is raising cash from private investors

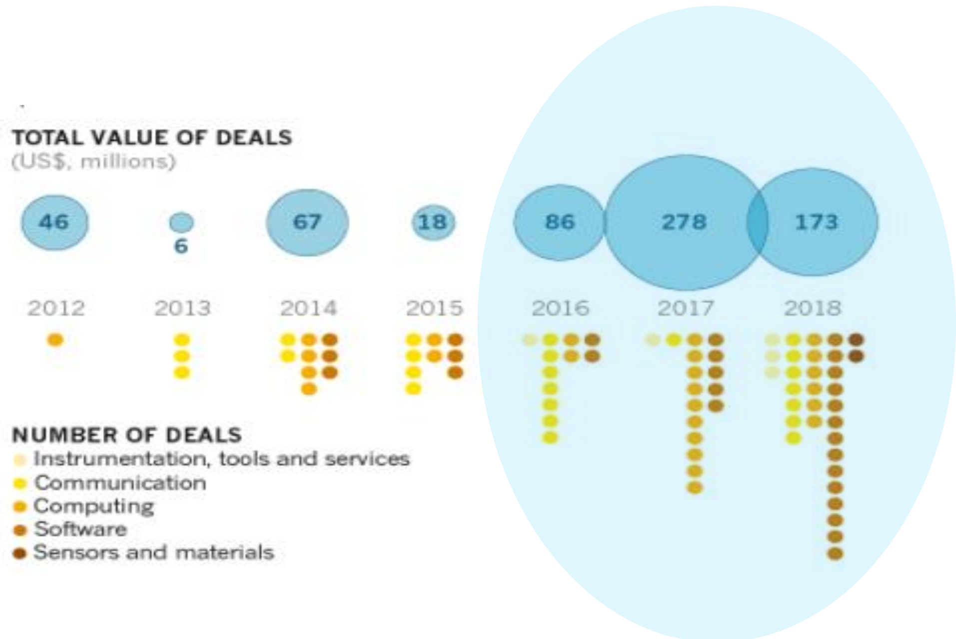

Figure 3: Timeline of quantum firms' financing and deals. Note that the 3rd and 4th categories received much of the interest (computing, software). Source: Nature. https://www.nature.com/articles/d41586-019-02935-4

[5] D-Wave. The Quantum Computing Company. https://www.dwavesys.com/

What we see here is an example of the "entrepreneurial state" (Mazzacato 2011) for quantum entrepreneurship. The state (US, UK, and others) has been instrumental in supporting and financing the research that then led to start-ups. In particular this is seen to be the case most in that area of quantum technology which is reported as closest to market (secure communications).[6]

It took twenty years for quantum technology to move from Peter Shor's seminal algorithm to a wide interest among large technology enterprises and governments. The USA and the UK are the protagonists of that acceleration. But other nations are prominent. By 2016, Canada begun to invest heavily in quantum research and was ranked 1st amongst G7 nations on investment in quantum research (Sussman et al. 2019). In the same year, the European Union announced the launch of a €1 billion flagship initiative on quantum technology7. Along with those in Italy, Spain and Sweden, the UK's universities, for example Cambridge, benefitted from funding.

For the period 2016-2019, the UK government through the Engineering and Physical Sciences Research Council (EPSRC), allocated £380m in quantum technology research with foci on quantum demonstrators, skills, and development of quantum research hubs in various part of the country. Research areas are used to describe EPSRC's portfolio of long-term research and high quality postgraduate training. Total theme funding amounted to £143 million (2.73% of the whole portfolio) across research areas (195M $ US). There were 36 grants in the Quantum Technologies theme[8].

A second phase of the programme was launched in 2019 with a similar spending profile[9]. The equivalent Canadian research council NSERC (National Sciences and Engineering Research Council) between 2006 and 2015 awarded CDN$ a comparable 267 million (approx. US$ 210 million). In the US, the 2018 National Quantum Initiative Act was passed: a 10-year plan with a US$1.2 billion commitment.

At the same time, investment from large enterprises like IBM, Google, and Microsoft and Amazon continues in the quantum technology space. In 2018 Google announced the creation of the 72-qubit chip called Bristlecone[10] and in 2019 IBM announced the first commercial quantum computer IBM Q Systems One[11] @20qubits. In 2019

[6] Considering that the telecom sector is focussing the attention on 5G/fiber optics deployments, quantum could play an important role in that.
[7] European Commission will launch €1 billion quantum technologies flagship | Shaping Europe's digital future (europa.eu) (accessed march 25 2021)
[8] https://epsrc.ukri.org/research/ourportfolio/themes/quantumtech/ (accessed September 16 2020)
[9] see note 7, but also Government Office for Science. 2016. The Quantum Age: technological opportunities.
[10] Emily Conover. 2018. *Google moves toward quantum supremacy with 72-quibt quantum computer*. Science News. https://www.sciencenews.org/article/google-moves-toward-quantum-supremacy-72-qubit-computer
[11] Aron, Jacob. 2019. *IBM unveils its first commercial quantum computer*. New Scientist. https://www.newscientist.com/article/2189909-ibm-unveils-its-first-commercial-quantum-computer/

Google claimed that its computer had reached quantum supremacy[12]. Companies in China e.g. Alibaba and Tencent and in Japan have also invested heavily[13].

Meanwhile, the number of quantum start-ups grew quickly: entrepreneurship activities in quantum technology saw an acceleration in the period 2016 through 2020 as shown in Figure 3.

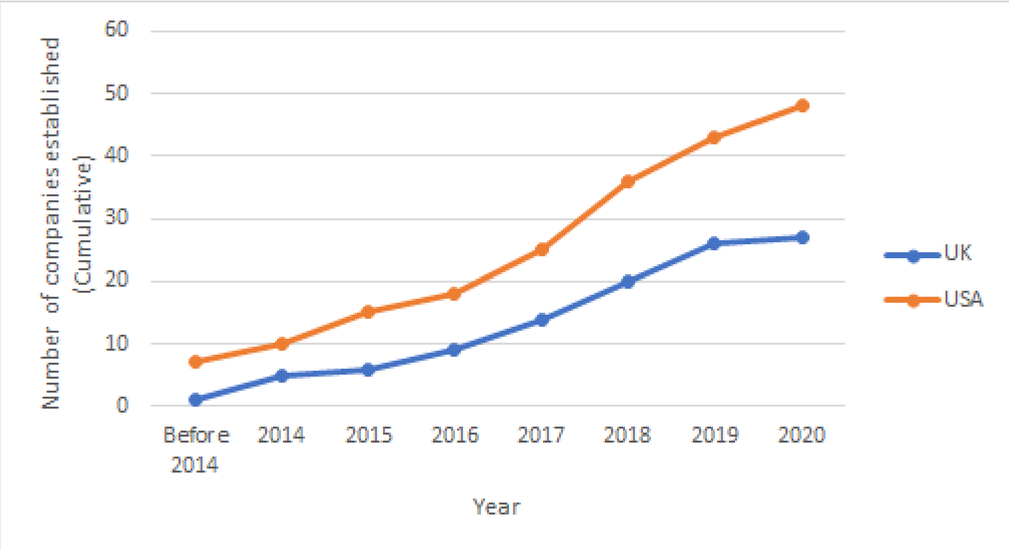

Figure 3. Cumulative growth of newly established quantum technology companies in the UK and the USA. Source: Authors' Data

From our own data, by September 2020 there were 48 quantum technology start-ups in the USA and 27 in the UK. At the end of 2015, there were 15 start-ups in the USA and 6 in the UK. As the technology policy in quantum got momentum, the number of newly established companies grew with a more decisive acceleration in the USA.

While the British-American difference in start-up numbers is not large, the difference in finance raised is much larger: by September 2020, USA companies raised US$926 million while the British raised US$109M. However, it has to be said that two US companies raised together US$706M - Rigetti Computing raised US$198M and PSI Quantum US$508M. Showing its maturity, the former company acquired QxBranch in 2019[14]. This is not the only acquisition happening in the US quantum technology market. Labber Quantum was acquired by Keysight Technologies in 2020.

The evolving quantum technology start-up landscape was established rapidly in the UK and the USA and was driven by a range of different kinds of actors. For example, by the start of 2019, according to an analysis by *Nature*, private investors had

[12] Google claims 'quantum supremacy' for computer - BBC News (Accessed April 25 2020)/
[13] Quantum gold rush: the private funding pouring into quantum start-ups (nature.com) (accessed march 25 2021)
[14] Rigetti Computing acquires QxBranch. https://www.prnewswire.com/news-releases/rigetti-computing-acquires-qxbranch-to-expand-full-stack-capabilities-300882977.html

funded at least 52 quantum technology companies globally since 2012. Many of them are spin-outs from university departments[15].

The evolving landscape has been driven both by policy intervention and the actions of the big corporates. We identify four recent developments. The first is that policies have moved from supporting research to also supporting go-to-market activities and skill promotion. This has created an incentive for researchers and experts to establish start-ups. The second is that there are areas of quantum technology more ready to go to market, particularly the part linked to secure communications and applications in security. Developments and deployments of 5G can benefit from quantum technology. Dedicated and secure communication solutions for specific applications (finance for example) can benefit from quantum. Therefore, there are markets that look at quantum with interest and in some cases trepidation. Third, the increasing attention of large tech enterprises on quantum technology is creating momentum. The pieces of news on quantum are more frequent, the topic appears associated to various type of players (fintech companies, MNOs).

The fourth is that the creation of "National Centres" and "Industry associations", while government-led are good for building networks. This is another important step towards building a community in quantum technology. Therefore, if these factors are supporting the first wave of quantum start-ups a policy question is whether governments should continue to support them, perhaps with a stronger focus on driving a quantum technology market? Alternatives are to stay on the "entrepreneurial state" or consider supporting more "public-private partnerships" involving the big players.

4.2 The Emergence of Quantum Industry Clusters in London and Washington

The role of the two capital cities in the development of quantum technology goes well beyond their natural role as policy centres. A consequence of that centrality is the strategic investments that the USA and the UK governments have dedicated to quantum technology. Additionally, there is also a market force giving major importance to city capitals: the fact the government is one of the major sectors attracted by the potential benefits of quantum technology in key areas of national security and public safety[16]. We ask, what these nascent industries look like in the two capital cities?

By 2020, both capitals have university research centres in quantum technology: Centre for Quantum Computing at George Washington University and the IBM-HBCU Quantum Centre at Howard University in Washington; the UCL Quantum Science and Technology Institute and the Imperial Centre for Quantum Engineering, Science and Technology in London.

Startup growth

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[15] Quantum gold rush: the private funding pouring into quantum start-ups (nature.com) (accessed March 25 2021)

[16] “From cloisters to cloud” The Economist, 26th of September. But also Quantum Computing Inc. Corporate Presentation. September 2020.

In terms of start-up formation, the two cities perform similarly as shown in Figure 4.

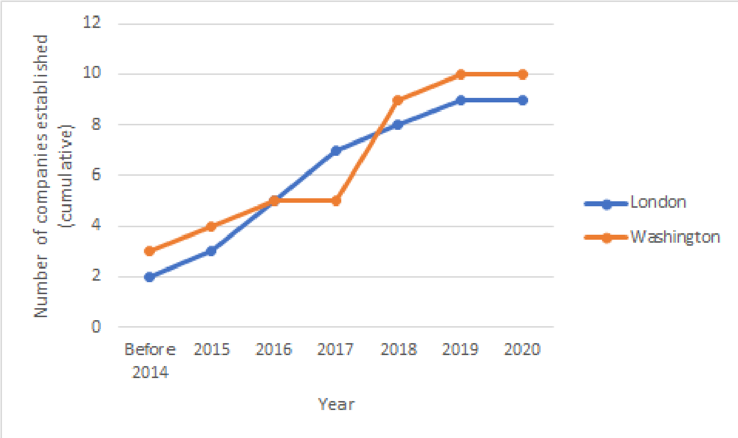

Figure 4. Cumulative growth of newly established quantum technology companies in London and Washington. Source: Authors' data.

By 2020 London had 9 start-ups and Washington 10 start-ups. The key difference is in the stage of development of these companies. The Washington-based firms are more mature in market terms. For example, IonQ is a respected firm claiming to have a very powerful quantum computer[17].

Riggetti is an interesting case of capitalizing on national security, government funding, and capital cities. Rigetti was founded in Berkeley California, but moved its global office to Washington and London, from where the company will lead a consortium for building the UK quantum computer[18]. In the data below, we add Rigetti to the Washington firms.

Startup Funding

The status of the London and Washington start-ups is analysed through CrunchBase (CB) two measures. The first measure is called Fund Index and it looks at the size of the investments received. The Fund Index is expressed in a Likert Scale from 1 to 5 (1 when funds raised are less or equal to US$1M up to 5 when funds raised are higher than US$40M). The second measure is the Visibility Index. It looks at the market presence in terms of partnerships, customers, and market announcements. It is also based on the CB Rank. The Visibility Index is expressed in a Likert Scale from 1 to 5, from 1 low market visibility to 5 very high visibility, that is possible using the CB Rank value. Figure5 shows the combination of these two indices for each company.

[17] IonQ recent claim on quantum computing. https://techcrunch.com/2020/10/01/ionq-claims-it-has-built-the-most-powerful-quantum-computer-yet/

[18] The Financial Times. Rigetti to build UK's first quantum computer. https://www.ft.com/content/cc9b866c-02fd-4a5c-b283-a17dd3dad6c3

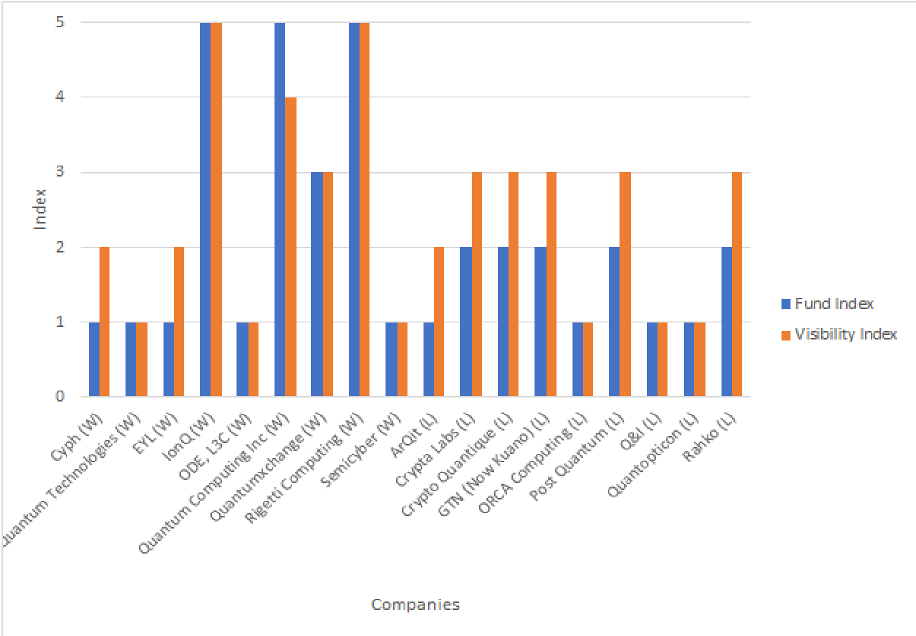

Figure 5. Fund and Visibility Assessment of Quantum start-ups based in London (L) and Washington (W). Source: Authors' survey using Crunchbase data.

The assessment displayed in Figure 5 shows the following:

- London-based companies are all in the early stage of finance with somewhat uniform low funding and low-medium visibility. The maximum investment that has been received to date is by Post-Quantum: US$ 11 million through 2020.
- The Washington group of firms is characterized by companies more advanced in terms of funding and market visibility. IonQ has US$ 82 million in funding through 2020 and QuantumXchange has US$ 23 million through early 2021.

Company size

Given the youth of this industry, firms are quite small. While, precise employment data is not available for all the companies, it is available in size bands. Figure 6 lists the companies in the two capitals with technology area of specialisation and size band as described previously.

City	Company name	Quantum technology area	Size
Washington	Cyph	Secure communication and computing	Micro
	Driven Quantum Technologies	Consultancy	Micro
	EYL	Secure communication and computing	Micro
	IonQ	Computing	Small
	ODE, L3C	Computing	Micro
	Quantum Computing Inc	Computing	Small
	Quantumxchange	Secure communication	Small
	Rigetti Computing	Computing	Medium
	Semicyber	Computing	Micro
London	ArQit	Computing - Security	Small
	Crypta Labs	Computing - Security	Micro
	Crypto Quantique	Computing - Security	Small
	GTN (Now Kuano)	Computing - Application	Micro
	ORCA Computing	Secure communication	Medium
	Post Quantum	Security	Small
	Q&I	Consultancy	Micro
	Quantopticon	Computing	Micro
	Rahko	Computing - Application	Micro

Table 1. List of companies in the city capitals. Technology area and size band.
Source: Authors, 2020
Micro (1-10 employees); small (11-50 employees); medium (51-100 employees).

The population of companies in the two capitals is mainly made of micro companies, with only one medium size company for each city: Rigetti Computing in Washington and ORCA Computing in London. The companies are also mainly involved in quantum computing activities with strong focus on cybersecurity.

On looking in detail, firms are often small consultancies or small developers. Smallness implies that there is little hardware development but instead the work is in application and algorithm development. One possible driver for these being in the capital cities is the closeness to government and its priorities, especially that for insurance against disaster in major government functions possibly following rapid deployment of successful hardware.

London is also the main financial centre of the UK whereas Washington is not. The main financial center in the US. New York has less than half the number of start-ups than Washington, perhaps indicating that as yet government is more interested in quantum that is the finance industry.

One prominent activity in Washington metropolitan area was in March 2021 University of Maryland-based spin-out IonQ went public with a $2 Billion Deal[19].

> "It's an area where the University of Maryland College Park has years of research acumen, helped by strategic investment and partnerships with the federal government, that led to advances in the lab. The university now has with 200 researchers working on the technology in a variety of disciplines, such as computing, sensing and imaging, and quantum communications. University of Maryland College Park President Dr. Darryll Pines said IonQ's move to go public is a validation that an investment in science and basic

[19] Quantum computing company IonQ plans to go public. Here's what it could mean for College Park - Technical.ly Baltimore (accessed March 25 2021)

> research can be a starting point for a path: Invest in science at a university, and people who can make discoveries. Then, they make discoveries that can in turn become products that power companies”.[20]

An employment analysis from a gender perspective

Looking at the founders, board members and advisors, we were able to do gender assessment. Figure 6 shows the total number of board members and advisors for each company, the number of female members and the number of female C-level members. The data is only available for 13 companies, 5 Washington-based companies and for 8 London-based companies.

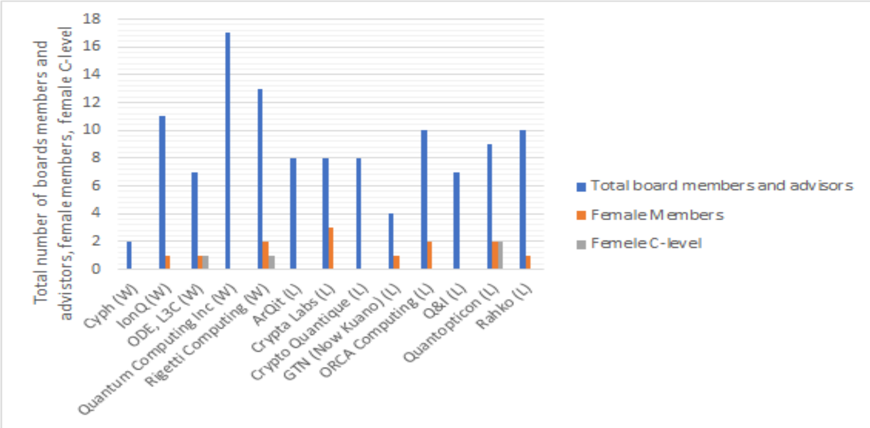

Figure 6. Gender analysis of the quantum technology companies.
Source: Authors’ data, 2020

There is a clear prevalence of men in the decision making process of the companies analysed. The highest rate of female presence is in the London-based Crypta Labs (37.5%), followed by the London-based Quantopticon (22.2%), whose CEO and CTO are female. The other two C-level members of the entire group are in Rigetti Computing and IonQ in Washington. If we look at the entire London group, 14% of board members and advisors are female. In the case of Washington, 8% of board members and advisors are female.   By comparison, the average percentage of women directors in the high-tech “Silicon Valley 150” firms was 18% in 2018 (Fenwick, 2018). Thus, these early quantum firms are somewhat more male-concentrated than the tech industry at large.

This is interesting because in both countries, national research and innovation funding agencies have a clear commitment to equality, diversity and inclusion policies. However, in this sector, that ethos does not appear to be operational at the company level thus perpetuating gender inequality in this sector in these two locations, although slightly less so in London. In California, by contrast, there is less inequality (but still at a high level), suggesting that there might be geographically variable cultural differences and a need for gender quality monitoring.

[20] Quantum computing company IonQ plans to go public. Here's what it could mean for College Park - Technical.ly Baltimore (accessed march 25 2021)

5. Conclusions

This survey paper has explored geographies of advance in quantum technology, how it has developed and why location matters for the trajectory of this emerging technology. This is now a global sector in which there is a history of collaboration and cooperation -- and now competition.

We found:

- A typical historical acceleration of growth in business/ start-up. The runway phase was longer than that for many technologies nowadays reflecting the delay in useful stable hardware.
- While there is substantial activity in the two capital regions of London and Washington, there is no locational dominance.
- Payback to universities --and by default their cities -- for their investment in research, is occurring though higher profile, providing training opportunities for students, attracting the highly skilled (spillover events) and also societal and public validation (Roberson 2021). Unsurprisingly, direct returns from IPR are yet to happen.
- The entrepreneurship wave the research has profiled should be framed within the development time of quantum technologies. On one side, there is the argument that to develop quantum computers which lie at the heart of all quantum technologies, requires more time – 5-10 years window for now. On the other side, the impact of quantum technology on areas such as secure communications and sensing is happening even before the reality. Quantum entrepreneurship policies should continue to have a long-term view on quantum computing start-ups and a more immediate view on segments more ready to be commercialised.
- It is a currently a male-led industry.

Policy implications and areas of debate

- Should the entrepreneurial state provide even more entrepreneurial finance?
- Should investors be allowed to move at their own pace?
- Are there specific initiatives (mentoring, coaching, incubating, accelerating) for quantum technology start-ups?
- Should research and innovation funding agencies take a more active stance on addressing equality, diversity and inclusion issues in the sector?
- Is there a need for international and government/industry collaborations in the area with an entrepreneurial focus?
- Do we need to communicate and educate industry and government more fully for instance by introducing quantum technology in the narrative of change led by 5G and AI?
- What analogies can be made with the past? Is the development of the Atom bomb a good analogy (a technology with sudden and immediate effects on many industries and realignment of world order) or is it more like the search for commercial exploitable activities on the moon.

If the sector matures and becomes more profitable, the issue of power between the public domain and the big techs becomes will emerge. Today the tech giants dominate

AI. Will the future world in which quantum is paramount be similarly dominated by giant (tech) firms? Conversely, is it the time to look seriously at collaboration between countries? In the space race it was a lack of commercial results that forced US/Russia collaboration. We do not yet see the true potential of China in the area. However, if the investment on quantum in China is equivalent to its investment in AI and 5G, the west could fall behind.

Future Research

Here are three areas we will investigate in future stages.

1. **Patents**. The patent data on quantum is still young. We will examine network data (including LinkedIn) of connections between stakeholders to see if there is a community in the two cities.
2. **In-depth study of quantum entrepreneurship.** The next step is to explore how to facilitate the new wave of quantum entrepreneurship. That step requires primary research. The primary research should assess the experience of the current start-ups, their journey, the challenges they have faced, the impact existing policy measures have had on their experience. The analysis of that assessment should then become the basis for the future quantum entrepreneurship policy.
3. **Challenges for quantum entrepreneurship.** In the UK, the state has now moved away from supporting research into quantum technology thus putting a break on technological advances in the science base. The major funding body, Innovate UK, makes it difficult for SMEs to obtain funding (paying grants in arrears and requiring matching funding) and onboarding of investors. Therefore the Entrepreneurial state in the UK has significant limitations. Future research could review the differences between the two countries and build possible scenarios for further development.

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Appendix A: Quantum firms list

The following list was compiled by the authors.

Companies in the United Kingdom

Company name	Web-address	Location within the UK
AegiQ	https://www.aegiq.com/	Sheffield
AppliedQbit	No website found	Surrey
ArQit	https://www.arqit.io/	London
Cambridge Space Technologies	No website found	Cambridge
Cambridge Quantum Computing Limited	https://cambridgequantum.com/	Cambridge
Crypta Labs	https://www.cryptalabs.com/	London
Crypto Quantique	https://www.cryptoquantique.com/	London
GTN (Now Kuano)	https://gtn.ai/index.html	London
KETS Quantum	https://kets-quantum.com/	Bristol
Nu Quantum	https://nu-quantum.com/technology	Cambridge
ORCA Computing	https://www.orcacomputing.com/	London
Oxford Ionics	https://www.oxionics.com/	Oxford
Oxford Quantum Cirtuits	https://oxfordquantumcircuits.com/	Oxford
PhaseCraft	https://www.phasecraft.io/	London and Bristol
Post Quantum	https://www.post-quantum.com/	London
PQShield	https://pqshield.com/	Oxford
Q&I	http://qandi.co.uk/#home	London
Quantopticon	https://quantopticon.co.uk/	London
Quantum Base	https://quantumbase.com/	Lancaster
Quantum Dice	https://quantum-dice.com/	Oxford
Quantum Impenetrable	https://www.dna-256.com/	Glasgow
Quantum Motion Technologies	http://quantummotion.tech/	Oxford
Qureca	https://www.qureca.com/	Glasgow
Rahko	https://rahko.ai/	London
Riverlane	https://www.riverlane.com/	Cambridge
TundraSystems Global	https://tsgl.xyz/	Cardiff
Universal Quantum	https://universalquantum.com/	Brighton

Companies in the United States of America

Company name	Web-address	Location within the USA
Aliro Quantum	https://www.aliroquantum.com/	Boston
ANKH.1	http://zigr.ltd/	West Covina
Atom Computing	https://www.atom-computing.com/	San Francisco
Bardeenq Labs	http://bardeenq.com/	Houston

Bleximo	https://bleximo.com/	San Francisco
Bra-ket Science	https://bra-ketscience.net/	Austin
BraneCell	https://branecell.com/	Boston
Cyph	https://www.cyph.com/	Washington
US Advanced Computing Infrastructure	https://www.chicagoquantum.com/#/	Chicago
ColdQuanta	https://www.coldquanta.com/	Denver
Dark Start Quantum Laboratories	https://darkstarqclabs.com/	
Driven Quantum Technologies	http://drivenquantumtechnologies.com/	Washington
EeroQ	https://www.eeroq.com/	New York
EYL	https://www.eylpartners.com/?ckattempt=1	Washington
High Precision Devices	https://hpd-online.com/	Denver
IonQ	https://ionq.com/	Washington
Labber Quantum	https://labber.org/	Boston
MagiQ Technologies	https://www.magiqtech.com/	Boston
ODE, L3C	https://odestar.com/	Washington
Polaris Quantum Biotech	https://www.polarisqb.com/	Durham
PSI Quantum	https://psiquantum.com/	San Franscisco
Qbitlogic	http://www.qbitlogic.com/	Atlanta and San Francisco
Qcware	https://qcware.com/	San Franscisco
Qrypt	https://www.qrypt.com/	New York
Qsimulate	https://qsimulate.com/	Boston
Quacoon	https://quacoon.com/home	
Quantum Circuits	https://www.quantumcircuits.com/	New York
Quantum Computing Inc	https://quantumcomputinginc.com/	Washington
Quantum Microwave	https://quantummicrowave.com/	Cohasset
Quantum Thought	https://www.quthought.com/	San Franscisco
Quantumxchange	https://quantumxc.com/	Washington
QuantyCat	https://www.quantycat.com/	Seattle
Qubittek	http://qubitekk.com/	San Diego
Qubit Engineering	http://qubitengineering.com/	Knoxville
QuDot	http://www.qudotinc.com/	San Francisco
QuEra Computing	https://www.quera-computing.com/	Boston
Qulab	https://qulab.com/	Los Angeles
Qunnect	https://www.quconn.com/	New York
QuSecure	https://www.qusecure.com/	San Francisco
QxBranch	https://www.rigetti.com/	Washington
Rigetti Computing	https://www.rigetti.com/	San Francisco
SeeQC	https://seeqc.com/	New York
Semicyber	https://semicyber.com/	Washington
Strangeworks	https://strangeworks.com/	Austin
Super.tech	https://www.super.tech/	Chicago
Turing	https://turingquantum.com/	New York
Xofia	https://xofia.io/	Houston
Zapata Computing	https://www.zapatacomputing.com/	Boston