The Commercial Prospects for Quantum Computing

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1: Overview of Quantum Computing

1.1 Quantum Computing – from the unthinkable to the inevitable

With the promise of performing previously impossible computing tasks, quantum computing has gained substantial research momentum over the last decade in the race to realise the world's first universal quantum computing machine. Such machines could perform quantum simulations that will help accelerate discoveries of novel materials and drugs. It will also revolutionise the way society encrypts its data, as quantum algorithms could break today's encryption schemes.

Currently, there are two categories of quantum computer. The first is a **Universal Quantum Computer**, and examples of its applications are described above. Much like a conventional computing processor, it can perform any kind of quantum computational operation. The second is the **Annealing Machine**, which is targeted in solving specific types of optimisation problems.

Both kinds of machine are made of quantum **bits** called **qubits**. A qubit has two distinct features that differentiate it from a regular bit: **Superposition** and **Entanglement**.

Bit A 'bit' is a basic unit of information, which in digital computers can either be 0 or 1 in value.

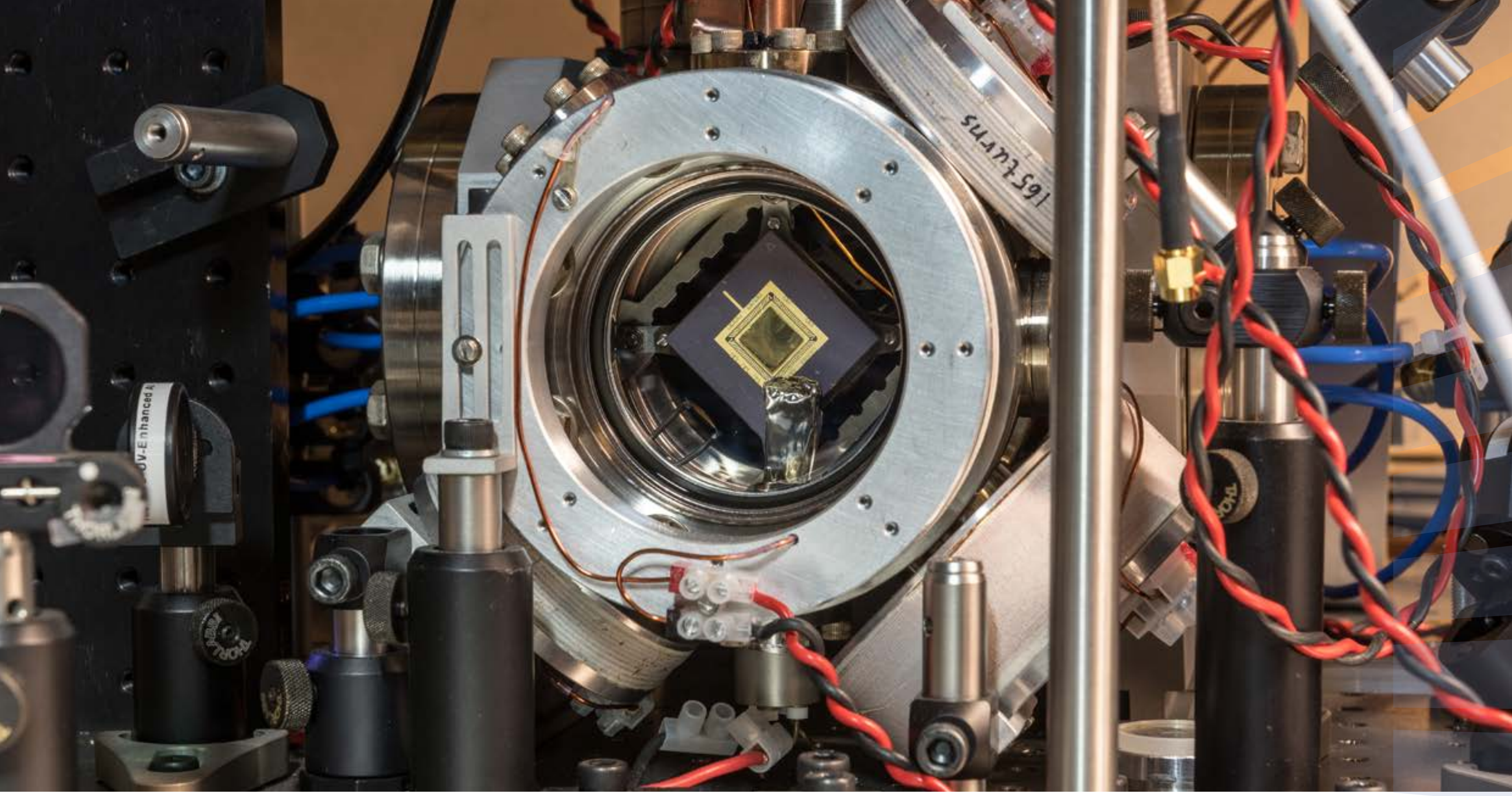
Qubit A qubit, or quantum bit, is a unit of quantum information, similar to a 'bit' in classical computing. However, unlike a bit, which can either be 0 or 1, a qubit can be 0 and 1 at the same time - a quantum superposition of both states. When multiple qubits are combined, they can store vastly complex data.

Superposition: In contrast to a regular bit, which can be either 0 or 1, a qubit can exist in both 0 and 1 states at the same time. The qubit may be 0 or 1, or have any ratio between them. A qubit can be thought of as an arrow that can point to any direction in three dimensional space: when it points up, the qubit is said to be in the 1 state; down is the 0 state, and any other direction is a combination of both. Superposition is a fundamental feature of quantum computing. In conventional (or 'classical') computing, a state of n bits (where n is a whole number) is described using n digits (zero or ones). In quantum computing it's more complicated, requiring 2^n-1 **complex numbers** to describe a state of n qubits. This means that an exponential number of classical bits would be needed to store the state of a quantum computer, even approximately.

Complex Numbers Complex numbers are of the form x+iy, where x and y are real numbers and i is the imaginary unit equal to the square root of -1

Entanglement: This is a counter-intuitive phenomenon where two or more different qubits can be connected, despite being physically apart. Einstein described entanglement as 'spooky action at a distance', since when qubits are entangled, the state of each qubit is not independent from the rest. Quantum computers exploit this phenomenon to provide a powerful speed-up in calculations.

Constructing a quantum computer with the level of precision required to create, manipulate and measure qubits is extremely challenging. Qubits are very sensitive to their local environment and any interactions can result in *decoherence*, or loss of information. There are currently three popular engineering approaches: **Ion-based** Qubits, **Superconducting** Qubits and **Solid-State Spin** Qubits.



Ion trap on a microchip for quantum computing set inside a vacuum system in the Oxford Physics Lab / *Stuart Bebb*

Ion-based Qubits

The Ion-based scheme uses trapped ions in a very low temperature environment as qubits, where the electronic state of each ion represents the qubit value. This can be measured from the photon (particle of light) emitted by the ion. For quantum computation, multiple ions can be entangled and this forms a single quantum computing node. The photons emitted by a node can be used to link and communicate with other nodes, forming a highly scalable networked architecture. Ion-based schemes are a mature technology achieving precision rates in excess of 99.9%, which makes them strong candidates to build a quantum computer. See §"4: Research Status" for more information.

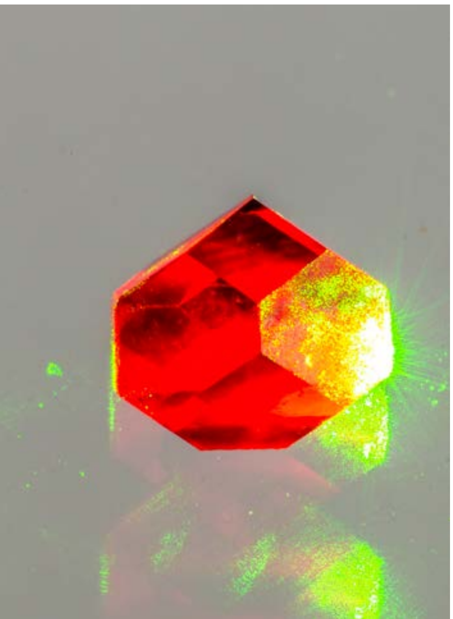
Ion An ion is an atom stripped of one or more electrons, giving it a positive charge, allowing it to be manipulated by electromagnetic fields.

Superconducting Qubits

In this scheme, special electrical circuits can behave like ‘artificial atoms’. These circuits are made from superconducting materials (such as aluminium and niobium), cooled to very low temperatures and operated at microwave frequencies. The qubit value can be stored in the number of superconducting electrons (charge qubit), in the direction of a current (flux qubit) or in oscillatory states (phase qubit).

Qubits can be entangled using microwave photons and the circuit may be linked to other circuits to form a scalable network. In addition, superconducting circuits have the advantage of being manufactured using existing integrated circuit fabrication techniques.

Diamond containing nitrogen vacancies fluorescing due to illumination with green light / *Jon Newland Photography*



Solid-State Spin Qubits

In this scheme, defects in a material such as diamond or silicon are used as qubits. For example, diamond is made up of a regular lattice of carbon atoms. If a carbon atom is missing this forms a vacancy. If a nitrogen atom is sitting in the lattice in place of a carbon atom and happens to be next to a vacancy, then this forms a special defect called a ‘nitrogen-vacancy’ (NV) centre.

The electrons associated with the NV centre have a property called ‘spin’ that describes their magnetic orientation. When they subjected to a magnetic field, the electronic spin can be up, down or in a superposition of the two. This then forms a qubit.

Unlike the previous schemes, NV centres do not require low temperature regimes and are natural light emitters, making the measurement process easier. However better manufacturing methods are needed to produce NV centres more reliably and in sufficient number.

This report examines the current commercial landscape and state of research for quantum computing, and demonstrates why quantum computing has moved from the unthinkable to the inevitable.

2: Current Commercial Activity

2.1 Commercial Investment

In 1982, Nobel laureate Richard Feynman asked: *"What kind of computer are we going to use to simulate physics?"* and *"Can you do it with a new kind of computer - a quantum computer?"*[1]. So the idea for a quantum computer was born, becoming an area of growing scientific interest. Seventeen years later, Geordie Rose co-founded D-Wave Systems Inc., the 'world's first quantum computing company', with initial seed capital provided by venture capitalist, Haig Farris. This first commercial investment into quantum computing began with a cheque for $4,059.50 Canadian dollars![2]

D-Wave has since raised over $120m [3] with a further funding round for $15m announced in May 2016 led by the Harris & Harris Group. They have established the fund 'H&H Co-Investment Partners, LLC' to allow a limited number of accredited investors to co-invest in D-Wave for the first time [4].

The disruptive potential of quantum computing is attracting growing interest and substantial investment from industry and governments globally. This is happening despite the understanding that a universal quantum computer is still years away from being commercially available.

Andrew Lockley writing for Exponential Investor, an online resource for technology investment, puts the case for quantum computing:

> *"There's a revolution coming in computing that has the power to disrupt society just as fundamentally as the first information revolution. This new generation of computers aren't just faster or better – they're completely, radically, different."* [5]

Atos, an international information technology services company, have illustrated the technological landscape and what they believe is the corresponding business impact (Figure 2.1). In their view quantum computing (circled) is an emerging technology from 2019 onwards, and its impact will be verging on transformational.

Some businesses are currently preparing themselves for the impact of quantum computing when it does arrive. The Commonwealth Bank of Australia (CBA) is one such institution which is investing heavily in quantum computing. CBA's Executive Manager of Technology Innovation, Dilan Rajasingham, succinctly said:

> *"We're not going to wait for the machine."* [6]

RBS Silicon Valley Solutions, part of the Royal Bank of Scotland Group, is an investor in 1QBit, a Canadian quantum software company. In January 2016, Head of RBS Silicon Valley Solutions, John Stewart, explained:

> *"The reason we invested was that we felt this was one of a fairly small number of cases where a technology was potentially so disruptive and so difficult to access, that making an investment and securing either a board seat or a board observer seat would give us a strategic advantage in exchange for a modest outlay."* [7]

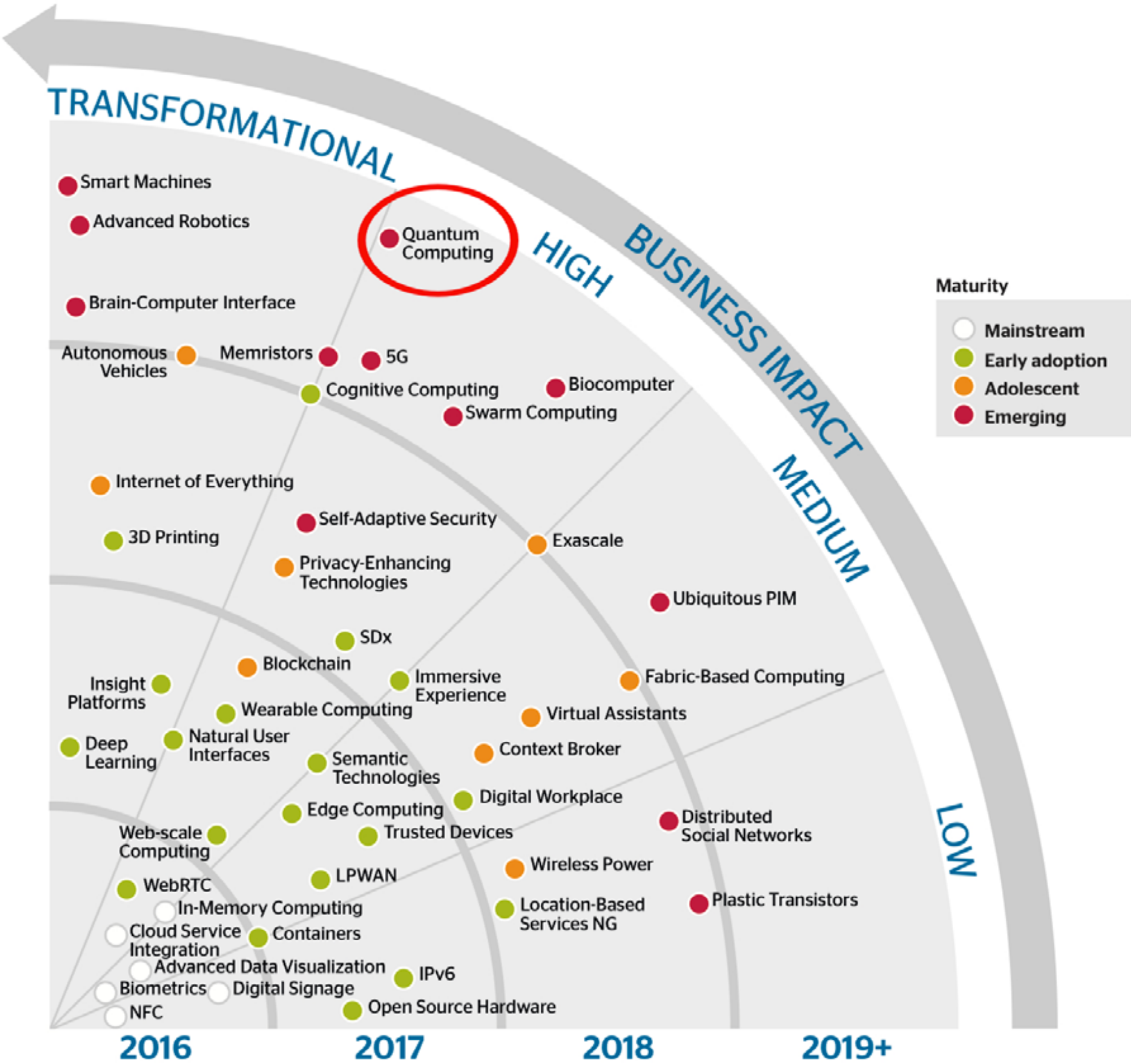


Figure 2.1: The technological landscape and impact on business / *Atos, 2016*

Despite its infancy, confidence in the future of quantum computing is growing. Market Research Media have projected the quantum computing market to exceed **USD 5 billion** by 2020 [8].

The companies with commercial interests specifically in the development of quantum computing range from start-ups to established technology multinationals. These are listed in Table 2.1, arranged by year founded and with approximate employee numbers (if available).

More information about each company is shown in Table 2.2, organised by country, and includes revenue and profit/loss figures (where known).

A detailed timeline for commercial activities in quantum computing is given in the Appendix.

Technology companies are recognising the strategic importance of quantum computing and investment activity has dramatically increased in recent years as Table 2.3 shows.

Microsoft has not publically disclosed the level of investment it has made into quantum computing. However, Dr Peter Lee, Corporate Vice President of Microsoft Research, speaking at the Structure Data conference in San Francisco in March 2016 [11], confirmed quantum computing was their largest area of research investment.

Table 2.1 Companies with commercial interest in Quantum Computing by year founded

Founded	Company	Employees	Objective
1911	Commonwealth Bank of Australia	46,000	Multinational Australian bank operating in New Zealand, Asia, North America and Europe.
1911	IBM	377,000+	Multinational technology and consulting company. Have now made a 5-qubit quantum computer available for worldwide use.
1948	Raytheon BBN	600+	Research and development company and military contractor.
1968	Intel	107,000	Multinational technology company and the world's largest semiconductor chip manufacturer.
1975	Microsoft	118,000	Multinational technology company most known for the Windows Operating System, MS Office software and the Xbox games platform.
1975	Telstra	36,000	Australia's largest telecommunications and media company.
1995	Lockheed Martin	126,000	Multinational aerospace, defense, security and advanced technologies company. D-Wave's first customer in 2011
1998	Google (now Alphabet)	57,000+	Multinational technology company known for Internet search and services, Android OS for mobile devices, and is building a quantum computer.
1999	Alibaba Group	36,000+	E-commerce giant with various online shopping services and cloud computing.
	D-Wave	100+	Quantum computing company. Customers include Lockheed Martin, Google, NASA and Los Alamos National Laboratory
2000	ATOS	100,000+	Multinational offering IT consulting, technology and services.
2012	1QBit	20	Quantum software start-up with blue-chip clients (Fortune 100).
	Qubitekk	–	Start-up to build a universal quantum computer, provide secure communications with quantum cryptography, and lab equipment for quantum scientists and engineers.
2013	Rigetti Computing	–	Start-up whose aim is to build a fault-tolerant gate-based solid state quantum processor [9].
	Quantum Valley Investments	–	Venture Capital company created by Blackberry founders for development and commercialization of quantum computing.
2014	Anyon Systems Inc	1-10	Software start-up providing tools to design and optimise quantum/nano electronics.
	Cambridge Quantum Computing Ltd	20	Start-up quantum software and services provider.
	TundraSystems Global Ltd.	–	Start-up seeking to build an all-optical processor for quantum computing.
2015	Quantum Circuits, Inc.	6	Start-up whose goal is to realise and sell the first quantum computers based on superconducting devices.
2016	Playground Global	–	Android creator, Andy Rubin is founder of Playground Global, a USD 300 million fund, which has invested in an unnamed quantum computing company [10].

Table 2.2 Companies with commercial interest in Quantum Computing by Country

Country	Company	Revenue (2015)	Profit/Loss (2015)
Australia	Commonwealth Bank of Australia	AUD 23,578m	AUD 9,063m
	Telstra	AUD 26,607m	AUD 4,305m
Canada	1QBit	–	–
	Anyon Systems Inc	–	–
	D-Wave	–	–
	Quantum Valley Investments	–	–
China	Alibaba Group	USD 12,293m	USD 3,923m
France	ATOS	EUR 10,686m	EUR 406m
UK	Cambridge Quantum Computing Ltd	–	GBP (717,945)
USA	Google (now Alphabet)	USD 74,989m	USD 15,826m
	IBM	USD 81,741m	USD 13,190m
	Intel	USD 55,355m	USD 11,420m
	Lockheed Martin	USD 46,123m	USD 3,605m
	Microsoft	USD 93,580m	USD 12,193m
	Quantum Circuits, Inc.	–	–
	Qubitekk	–	–
	Raytheon BBN	USD 23,247m	USD 3,013m
	Rigetti Computing	–	–
Wales	TundraSystems Global Ltd.	–	–

Table 2.3 Companies investing in Quantum Computing

Date	Company	Amount	Notes
1999-2016	D-Wave	USD 141.81m	Investors include: Harris & Harris Group, Draper Fisher Jurvetson, Goldman Sachs, In-Q-Tel, Bezos Expeditions
2006-current	Microsoft	Not disclosed	Microsoft is researching into quantum computing with multi-million dollar investment
2009-current	Google (now Alphabet)	Not disclosed	Google are building a quantum computer as well as buying a D-Wave system with NASA and USRA
2011-current	Lockheed Martin	Not disclosed	D-Wave's first customer.
2012	Raytheon BBN	USD 2.2m	IARPA funding to research integration of hardware and software for a quantum computer
2013	Quantum Valley Investments	USD 100m	Quantum computing fund established by co-founders of Blackberry.
2014	IBM	USD 3 billion	Investment over 5 years for research into nano-sciences including quantum computing.
	Rigetti Computing	USD 3m	Main investor is Y Combinator
	Qubitekk	USD 3m	Grant awarded from US Department of Energy
2015	1QBit	Not disclosed	Investors are CME Group (Series A) and RBS Solutions
	Alibaba Group	CNY 150m	Five year investment into quantum computing research from 2015.
	Cambridge Quantum Computing Ltd	USD 50m	Grupo Arcano investment over 3 years
	Commonwealth Bank of Australia (CBA)	AUD 15m	Investment in quantum computing research
	IBM	Not disclosed	IARPA grant awarded to IBM to advance research into universal quantum computer.
	Intel	USD 50m	Invests in Delft University of Technology and TNO, the Dutch Organisation for Applied Research
	Playground Global	USD 300m	Venture fund founded by Android creator Andy Rubin, Peter Barrett, Matt Hershenson and Bruce Leak.
	Telstra	AUD 10m	Investment in quantum computing research
2016	Alibaba Group	USD 1 billion	Alibaba Cloud forms strategic partnership with Nvidia for cloud computing and quantum computing.
	Quantum Circuits, Inc	–	In the process of fundraising
	TundraSystems Global Ltd	–	In the process of fundraising

Quantum computing is no longer in the realm of science fiction, and as the global race to build a quantum computer heats up, the commercial landscape will continue to change, presenting new investment opportunities as a result.

The promise of quantum computing is both exciting and inspiring. The following quotes from industry figures reflects this optimism.

Brian Krzanich, Chief Executive of Intel, said in a blog article in September 2015:

> *"I'm excited about the role that Intel's greatest minds and expertise can play in shaping this impactful technology, and I hope you are too. Quantum computing holds the promise of solving complex problems that are practically insurmountable today, changing the world for the better. That's a technology I think we'll all be incredibly proud to play a part in developing."* [12]

Vern Brownell, Chief Executive of D-Wave, believes the quantum computing era has begun. In an interview with CIO.com (June 2016), Brownell said:

> *"We're at the dawn of this quantum computing age. We believe we're right on the cusp of providing capabilities you can't get with classical computing…*
>
> *We're at the bleeding edge today. It's a very exciting time to be in the middle of all this."* [13]

Commercially available D-Wave 2X Quantum Computer / *D-Wave Systems Inc.*

2.2 Open Source Activity

Open Source Software (OSS) is computer software that is free to download and use, includes the source code, and can be modified or redistributed under an 'open source license', of which there are various kinds. A list is available from the Open Source Initiative [14], who are an organisation dedicated to promoting OSS.

The range of OSS is vast in scope and has been created by individuals, companies or collaborative groups of varying sizes, who may also have global distribution. Examples of popular OSS applications are shown in the Appendix.

The main economic benefit of using OSS is cost saving. For example, in 2009 the 'IT @ School' project of Kerala, India, replaced Microsoft Windows software with an OSS equivalent (Linux) on 50,000 desktops in 2,800 schools across the state. This led to an overall saving of USD 10.2 million in licensing costs [15].

Quantum computing OSS is also available with 49 currently accessible projects dating from 1999 to July 2016. The majority of these are from universities, with companies including Google, Microsoft and Toronto based Artiste-qb also contributing.

OSS for quantum computing encompasses tools for mathematical computation applications: including Matlab and Mathematica; as well as quantum algorithms and quantum simulators in a variety of computer languages (see Table 2.4).

Microsoft 'Liqui|>' by Microsoft and 'QuTip' are two examples of OSS toolkits for quantum computing. These help make programming easier and more accessible using high-level languages (F# for Liqui|> and Python for QuTip). However, using these tools requires familiarity with quantum physics.

Dave Wecker, Architect in the 'Quantum Architectures and Computation Group' (QuArC) at Microsoft Research, who helped developed Liqui|> says:

> *"This is the closest we can get to running a quantum computer without having one...*
>
> *This isn't just, 'Make the qubits.' This is, 'Make the system.' "* [16]

OSS has an important role in teaching and training the current and next generation of quantum scientists, engineers and entrepreneurs.

OSS can also lead innovation, not only to improve quantum algorithms, but facilitate the creation of more complex quantum-based applications, as the knowledge, language and tools become more sophisticated and spread to a wider audience.

Just as OSS is enabling businesses to do new things in the digital age, what can OSS for quantum computing achieve in the quantum era? Only time will tell.

Table 2.4 Open source resources (1999 to July 2016) with corporate activity highlighted in blue

Release	Name	Language	Origin (University, Individual or Company)
1999	Shor Algorithm	C++	University of Illinois, USA
2000	QuCalc	Mathematica	Universite de Montreal, Canada
2000	Quantum-Superpositions	Perl	Damian Conway
2001	QMatrix	Mathematica	University of Potsdam, Germany
2002	Quantum-Entanglement	Perl	Alex Gough
2002	qoToolbox	Matlab	University of Auckland
2004	QGame++	C++	Hampshire College, USA
2004	CHP	C	Berkeley, USA
2005	qsims	C++	Travis Beals
2005	Quack!	Matlab	Peter Rohde
2005	Quantum Information Programs	Mathematica	Carnegie-Mellon University, USA
2006	Qubiter	C++	Artiste-qb, Canada
2007	Zeno	Java	Federal University of Campina Grande, Brazil
2007	QCF	Matlab	Oxford University
2007	QDD	C++	David Greve
2007	LanQ	C-like	Hynek Mlna ik
2009	Cove	MS NET	Colorado Technical University, USA
2009	PyQu	Python	Google, USA
2009	Quantum-Octave	GNU Octave and Matlab	Polish Academy of Sciences, Poland
2010	QuBit	C++	Steven Goodwin
2010	jQuantum	Java	Fachhochschule Südwestfalen
2011	QLib	Matlab	Tel-Aviv University, Israel
2011	QuCoSi	C++	Frank S. Thomas
2011	Quantum	Mathematica	Tecnológico de Monterrey, Mexico
2012	Eqcs	C++	Peter Belkner
2012	Squankum	Java	Johns Hopkins Center for Educational Resources.
2012	TRQS	Mathematica	Polish Academy of Sciences, Poland
2012	QI	Mathematica	Polish Academy of Sciences, Poland
2013	Libquantum	C	Hannover, Germany
2013	Q++	C++	Cybernet Systems Corp
2013	Quantum Construct	C++	Shekhar Suresh Chandra.
2013	Qitensor	Python	Dan Stahlke
2013	qMIPS101	Java	University of Seville, Spain
2013	sqct	C++	University of Waterloo, Canada
2014	QuanSuite	Java	Artiste-qb, Canada
2014	QCL	C-like	AIT Austrian Institute of Technology
2014	Quantum Computing Playground	qScript	Google, USA
2014	QWalk	C	University of Illinois, USA
2014	jsqis	Javascript	University of California, USA
2014	Quipper	Haskell	Dalhousie University, Canada
2015	QuTip	Python	RIKEN, Japan; University of Michigan, USA
2015	SpinDec	C++	University College London, UK
2015	Quantum++	C++	University of Waterloo, Canada
2015	QDENSITY	Mathematica	University of Pittsburgh, USA
2015	QUIBIT4MATLAB	Matlab	WIGNER RCP, Hungary
2016	QETLAB	Matlab	University of Waterloo, Canada
2016	Liqui|>	F#	Microsoft Research, USA
2016	Quantum Fog	Python	Artiste-qb, Canada
2016	Qubiter	Python	Artiste-qb, Canada

2.3 Patent Activity

Patents are one indicator of innovation and looking at the patent landscape for quantum computing gives a valuable insight into activity in this area.

A summary of the world-wide patents for quantum computation between 1985 and 2013 is shown below.

Number of patent families	839
Number of patent applications	1,995
Peak publication year	2005
Top applicant	D-Wave Systems
Patent assignees	860
Priority countries	23
Top Country	USA

Source "Quantum Technologies: A patent review for Engineering and Physical Sciences Research Council" [17]

Figure 2.2 shows a comparison by inventor country and the number of patent publications in quantum computation. Please note that a patent publication is not a granted patent.

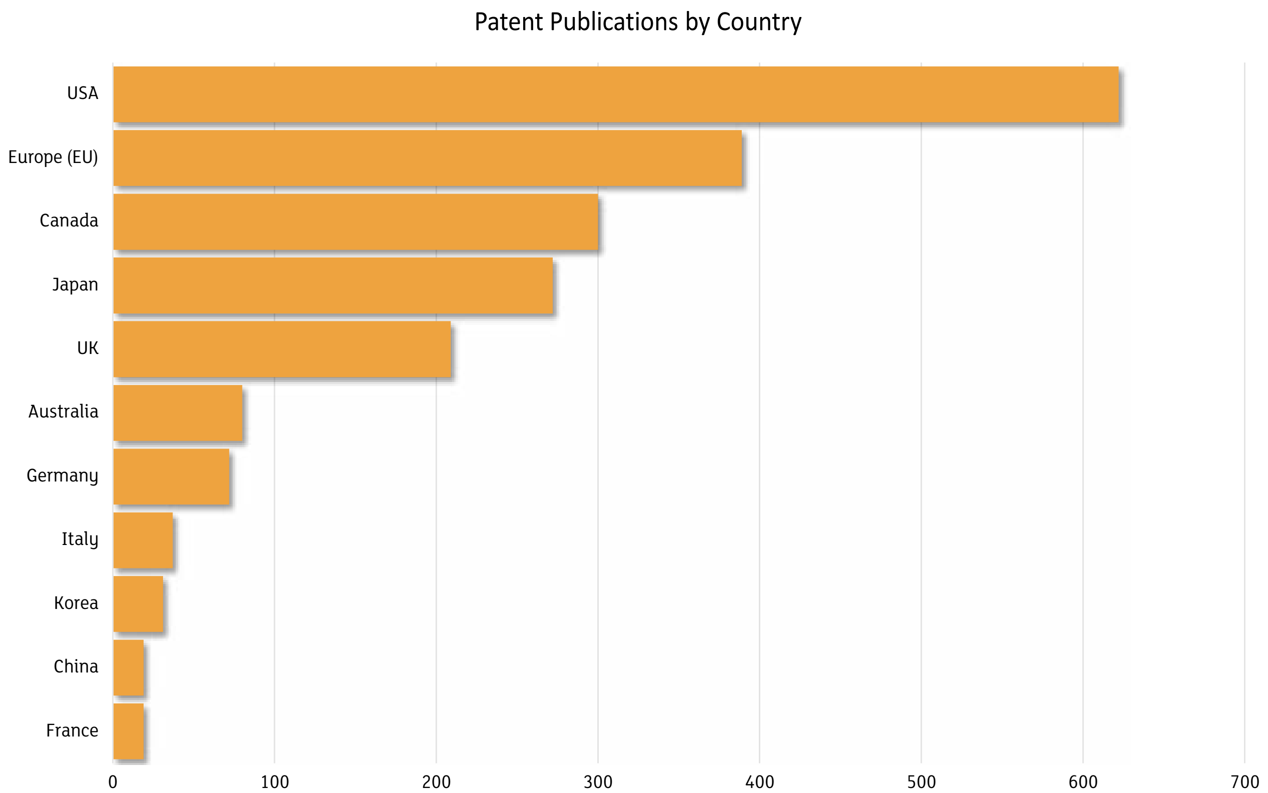


Figure 2.2: Number of patent publications by country in quantum computation 1985-2013

The USA tops the list followed by the European Union, Canada, Japan and the UK.

Figure 2.3 shows the most active organisations, with D-Wave Systems (Canada) clearly leading the field, followed by Hewlett Packard, the Japan Science & Tech Agency and Toshiba.

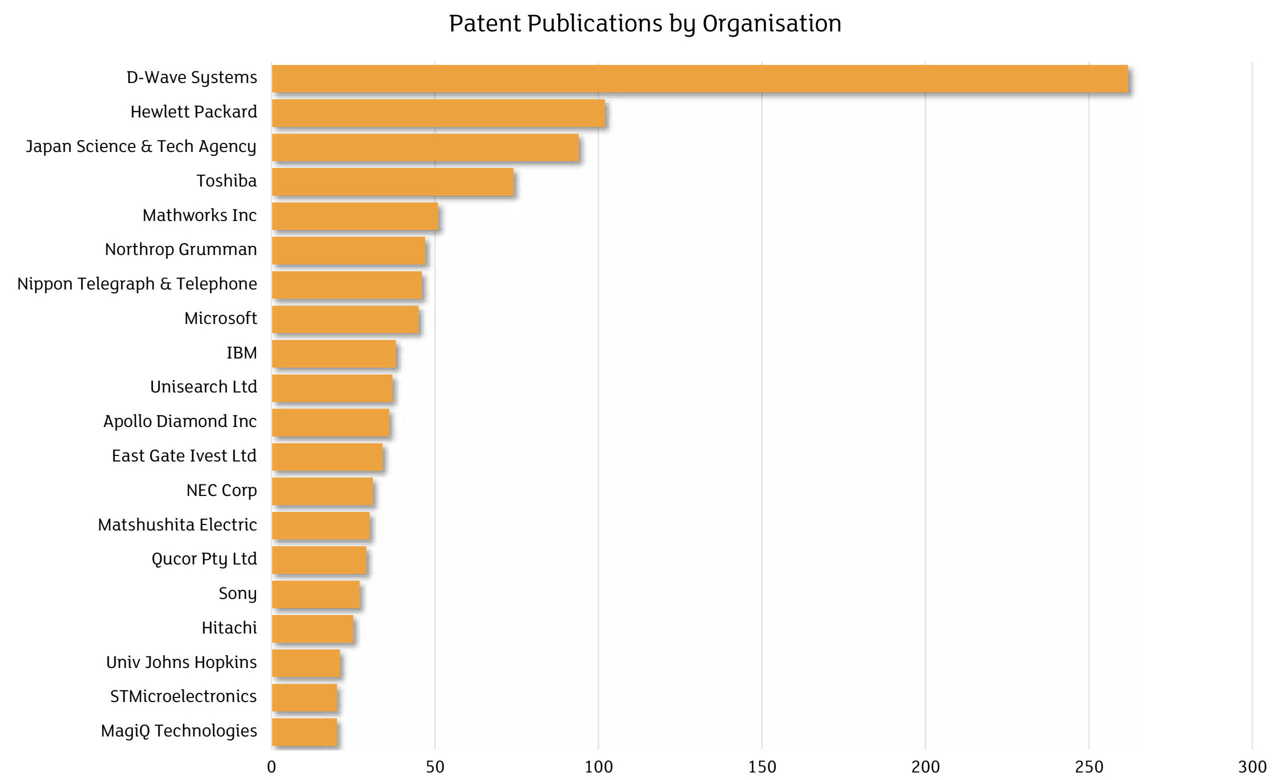
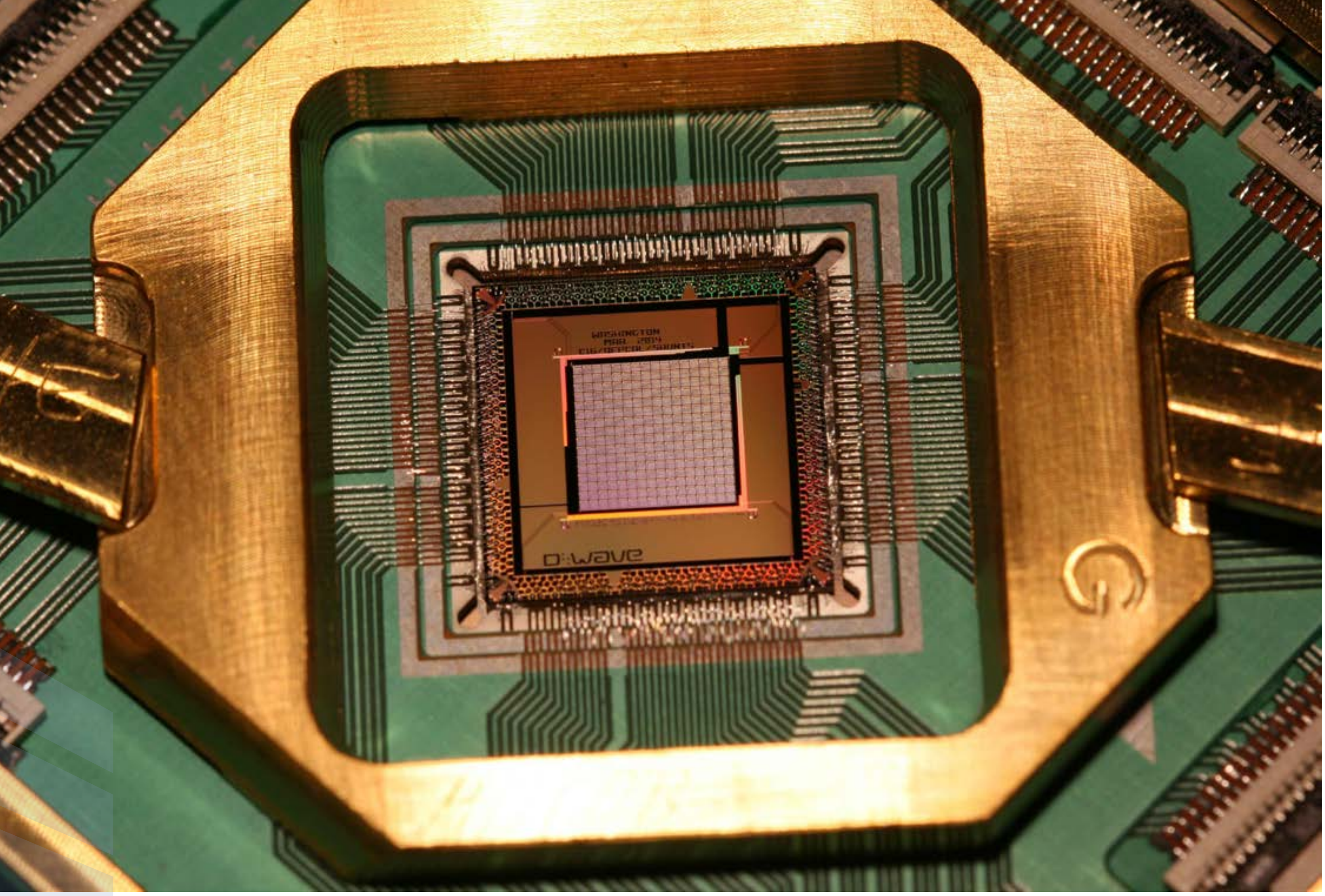


Figure 2.3: Top patent publications by organisation in quantum computation 1985-2013



D-Wave Systems are leading the field in patents for quantum computation http://www.dwavesys.com/resources/media-resources

Although filing for a patent takes time, there are many benefits to doing so. A patent stops others from copying, manufacturing, selling or importing the invention, without the patent holder's permission. Patents give a competitive advantage by keeping potential competitors at bay for a pre-determined period. An inventor can make use of the patent directly or license it.

As well as obtaining patents, another commercial activity is selling them as they are assets. USA based MagiQ Technologies, Inc. is one such example. In September 2015 MagiQ Technologies announced that they had retained Adapt IP Ventures, LLC to market its portfolio of quantum computing and security patents.

Brian Bochicco, Vice President of Adapt IP Ventures said:

> *"The large investments currently being poured into the quantum computing and cryptography technology segments from industry leaders such as Google, Intel, IBM, Microsoft and Alibaba only help to confirm the market relevancy of the MagiQ portfolio. As such, we believe that we will receive interest in this IP portfolio not only from these larger players, but also from focused quantum groups, network security companies, and investment funds."* [18]

Patents can cover all aspects of the design, construction and operation of a quantum computer. In addition, spin-out technologies from research efforts into quantum computing may be commercialised and protected by patents.

There are disadvantages to patents. It can take a long time for a patent to be granted. A patent is expensive and there is an annual fee to consider to prevent it from lapsing. Patents are public, so anyone can see the details of the invention – including competitors! It may be a better strategy to operate stealthily instead. Finally, a patent may need defending if infringed, leading to substantial litigation costs with no guarantee of success.

3: Market Status

3.1 Introduction

The economic impact of quantum computing can be considered from both research and commercial perspectives.

Research in quantum computing by universities and companies is generating revenue for suppliers on a local, national and global basis, through the purchase of specialist equipment and components.

One such supplier is M-Squared Lasers, a Scottish company founded in 2005, who provide lasers for the scientific, medical and defence sectors. Quantum computing is a growth area for the company. In an interview with The Telegraph newspaper in June 2016, Chief Executive, Dr Graeme Malcolm OBE said:

"In the UK we've got the best organised push into quantum in the world."

For the 12 months to May 2016, the company has seen growth of 40% and revenues of GBP 10 million, with more than half of sales to the USA [19].

Figure 3.1 IBM 5 qubit processor
IBM Research
https://www.flickr.com/photos/ibm_research_zurich/26093923343/

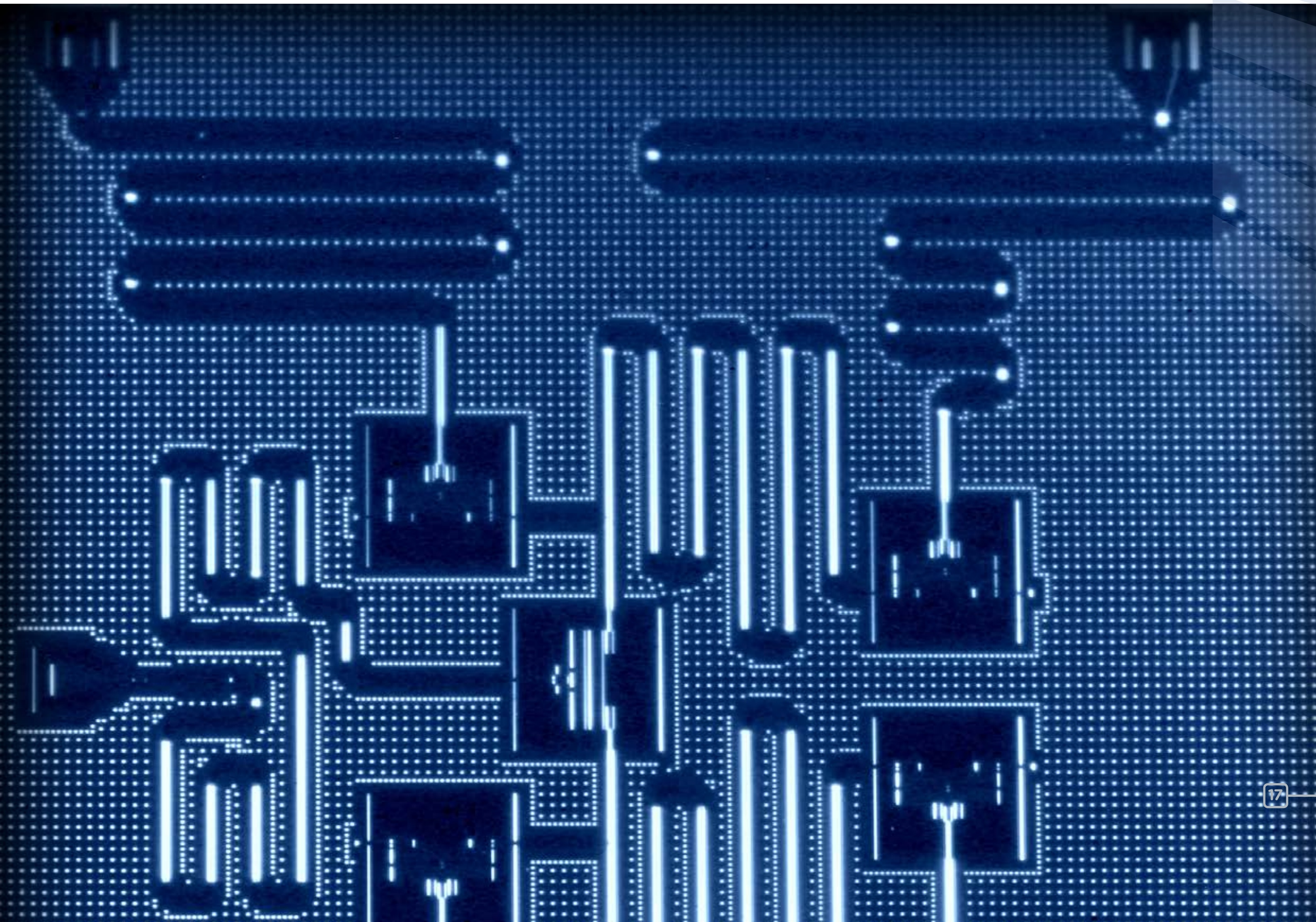


Table 3.1 Start-up companies in quantum computing from 2012-2016, grouped by year

Date	Company	Amount	Notes
2012	1QBit	Canada	Application software and tools for quantum computing. Quantum ready software development kit to be released in Q3 2016. Clients include Fortune 100 companies.
	Qubitekk	USA	Developing a quantum computer, provider of secure communications with quantum cryptography, and lab equipment for quantum scientists and engineers.
2013	Cambridge Quantum Computing	UK	Software and tools for quantum computing, including the **ti|ket>** simulator.
	Rigetti Computing	USA	Developing a fault-tolerant gate-based solid state quantum processor
2014	Anyon Systems, Inc	USA	Provider of software tools to design and optimise quantum/nano electronics
	Fathom Computing	USA	Operating in stealth mode
	QbitLogic	USA	Quantum computing software company with a general focus on AI algorithms
	QCWare	USA	Application software and tools for quantum computing
	QxBranch	USA	Quantum consultancy spin-off from Lockheed Martin and Australian defence firm Shoal Engineering.
2015	Artiste-qb	Canada	Quantum software and tools
	Quantum Circuits, Inc	USA	Developing quantum computer based on superconducting devices
2016	H-Bar Quantum Consultants	Australia	Quantum consultancy launching Q3 2016
	IonQ	USA	Spin-off from University Maryland and Duke University. Quantum computing with ion traps.
	Sparrow Quantum	Denmark	Spin-off from the Niels Bohr Institute's Quantum Photonics Lab, Copenhagen. Single photon source chip.

Alphabet, Microsoft and IBM are investing heavily into building a universal quantum computer, with each company taking their own technical approach.

In May 2016, IBM surprised the community by announcing public access to their experimental quantum computing platform. The "IBM Quantum Experience" creates a 'virtual lab' for researchers and students accessible through the cloud. Their quantum computer has only 5 qubits (Figure 3.1), but nonetheless demonstrates joined up thinking in that they will develop an ecosystem of users around their technology [20]. The IBM share price rose 20 cents (to USD 144.33) at the news.

On the commercial front, the only quantum computer that can be purchased today is produced by D-Wave Systems, Inc. Their latest generation quantum annealing machine, the D-Wave 2X™, has 1,000 qubits, consumes 25 kilowatts of power, and costs in the region of USD 15 million. In September 2016, D-Wave announced its new 2,000 qubit processor, which they claim to be 500-1000 times faster than its predecessor and will ship in 2017 [21].

Although the market is at an early stage of development, there have been encouraging signs of growth through a wide range of start-ups (Table 3.1) providing consultancy, software and devices of various kinds. The presence of established firms in this space, such as Hewlett Packard and Lockheed Martin, helps build confidence, and strategic partnerships and initiatives to stimulate the market have begun.

3.2 Established Firms in the Quantum Computing Space

Founded in 1914, **Booz Allen Hamilton**, an American management consultancy, offers quantum computing consultancy for government and business clients on a range of real-world problems. These include: system & network optimisation, vehicle routing, logistics, job scheduling, drug discovery, manufacturing, system design and verification & validation [22].

Information technology giant **Hewlett Packard** (founded in 1939), formed a quantum information processing group based in Bristol, UK in 1995. Areas of interest include: quantum computation, quantum communications, quantum teleportation and quantum cryptography [23].

Research and development company **Raytheon BBN** (founded 1948), has established a quantum information processing group in Cambridge, Massachusetts, USA, in 2009. They are working on next generation quantum sensors, quantum communications and quantum computing. Their customers include the US Navy, UK Royal Air Force and the Canadian Navy [24].

Northrop Grumman (founded in 1994) is a global aerospace and defence technology firm, whose Advanced Concepts and Technologies (AC&T) organisation is developing advanced computing technologies, which includes quantum computing [25].

Global aerospace and defence firm **Lockheed Martin** (founded in 1995), established the "USC-Lockheed Martin Quantum Computation Center" in partnership with the University of Southern California in 2011. Lockheed Martin is D-Wave's first customer and the facility houses the D-Wave 2X™ [26].

International IT Services company **Atos** (founded in 1997), launched "Atos Quantum" in November 2016. This is an initiative to develop and market solutions for quantum computing, as well as quantum safe cyber security products [27].

3.3 Strategic Partnerships and Initiatives

Some companies have formed strategic partnerships to create an ecosystem for quantum applications. D-Wave has partnered with DNA-SEQ Alliance, Inc., a company founded in 2013, whose goal is to revolutionise cancer treatment and drug discovery [28].

In May 2016, D-Wave and 1QBit, together with experts in the Finance industry, announced the "Quantum for Quants" online community, to foster collaboration and provide tools to help solve complex problems in Finance [29].

In a press release, Landon Downs, President and co-Founder of 1QBit said:

> *"Sharing the tools we've built with the community will create a better understanding of how quantum computing can be applied to finance, and in turn will inspire the development of additional tools that enable these new applications."* [30]

3.4 The Road Ahead

Quantum computing is gaining more awareness and with this comes opportunities and challenges.

We anticipate the growth in start-ups to continue. More jobs are already being created requiring quantum physicists, mathematicians, computer scientists and quantum engineers.

For example, in a recent job advertisement by Northrop Grumman (August 2016), the qualifications for Physicists for the Advanced Concepts and Technologies organisation, stated: *“Familiarity with superconducting qubits, quantum computing, and classical computer science desired”*.

In June 2016, the Professional Services division of D-Wave advertised for a ‘Quantum Software Engineer’ to support D-Wave’s users and develop software for customer applications. The applicant should have experience in *“machine learning, verification & validation, quantitative finance, or applied discrete mathematics in an industrial context.”*

Addressing the skills required for quantum computing and training the next generation ‘quantum workforce’ are essential.

A challenge for businesses is to attract and retain talented people, especially in a global market.

A more immediate challenge is helping industrialists understand the impact of quantum computing in their sector. Why is quantum computing relevant? What preparations are necessary? What actions are required and when? What is the financial cost? What is the cost of failing to act?

Answering these questions requires a multi-disciplinary approach, access to expertise and extensive resources (such as research facilities or High Performance Computing for quantum simulations). In other words, a Quantum Computing Centre of Excellence.

4: Research Status

Since the first concept of quantum computing over 3 decades ago [31], this field has gained substantial research momentum over the last decade. Research groups all over the world are in the race to realise the world's first universal quantum computing machine.

It's a Global Effort: Many countries including Australia, Austria, Canada, China, France, Germany, The Netherlands, Japan, Switzerland, Singapore, Spain, USA and the UK have research programmes on Quantum Computing with substantial funding.

For example, since 2002, the Institute for Quantum Computing (IQC) in University of Waterloo, Canada, attracted more than $300 million in investments from the Government of Canada and private investors for pursuing quantum technologies.

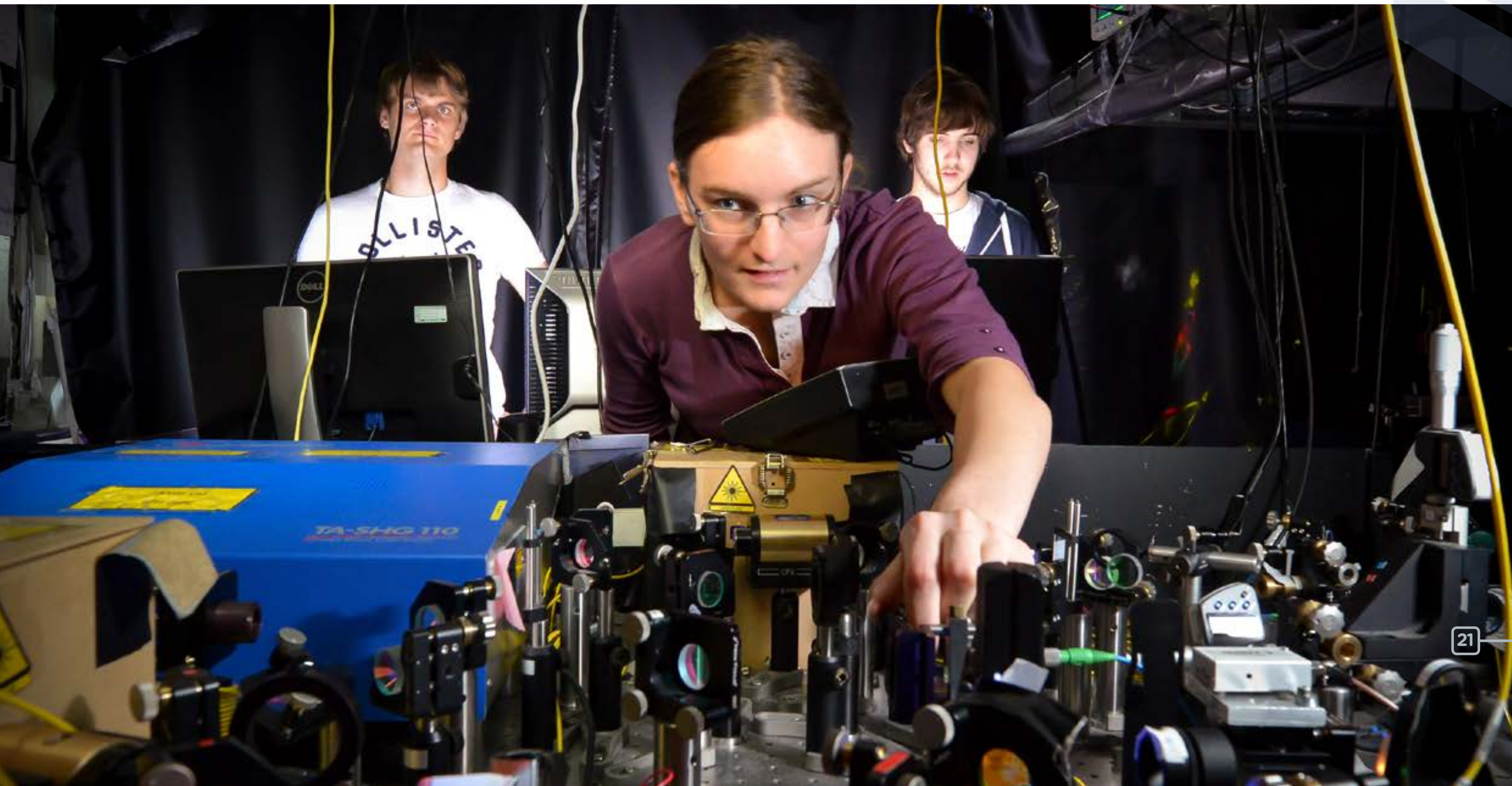
Since 2007, Singapore government invested over SG$195 million into quantum technologies, of which quantum computing is a major research area.

In the US, since 2010, the Intelligence Advanced Research Projects Activity (IARPA) invested heavily in several major quantum computing projects [32], including 'Coherent Superconducting Qubits (CSQ)', 'Logical Qubits (LogiQ)', 'Multi-Qubit Coherent Operations (MQCO)', 'Quantum Computer Science (QCS)' and 'Quantum Enhanced Optimization (QEO)'. Although the amount of investment is not disclosed, from the size of these programmes, the estimated spend is over $200 million.

In 2014, the UK government invested £38 million into a Quantum Computing initiative led by University of Oxford [33].

In 2015, Intel invested US$50 million into the Dutch consortium for Quantum Technology, QuTech, based in Delft [34]. Also in 2015, Alibaba has formed a joint venture the Chinese Academy of Sciences, investing $5 million per year for the next 15 years to develop quantum computing. This is a total of $75 million [35].

Ion trap experiment at the University of Sussex



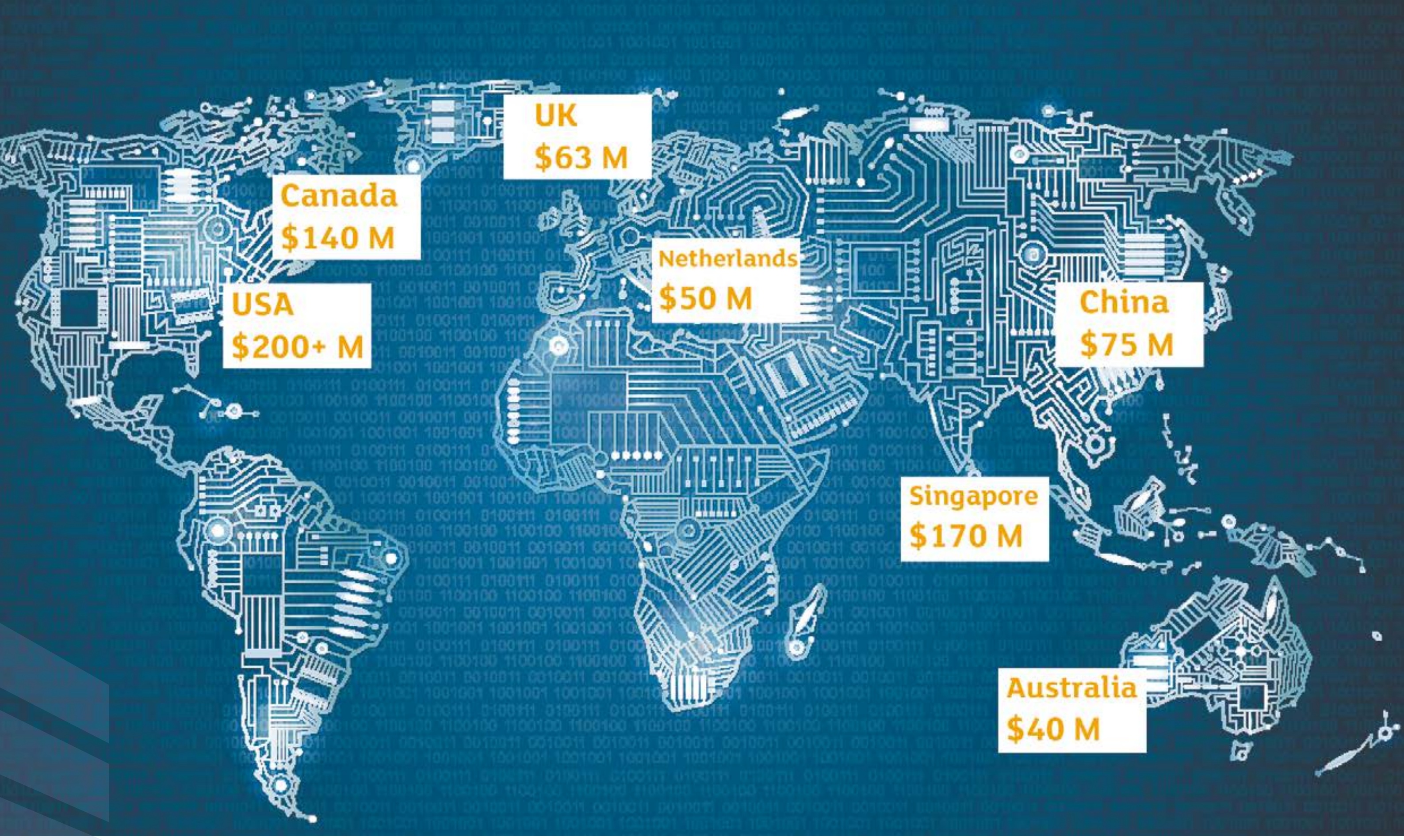


Figure 4.1: Examples of major investments on Quantum Computing research programmes.
The monetary figures shown are estimated values invested in these major programmes from 2010 to 2016.

In July 2016, the Australian government made an AU$46 million investment into a Quantum Computing programme based at the University of New South Wales [36]. Also in 2016, a €1 billion flagship programme for quantum technologies was announced by the European Union, where quantum computing has been identified as one of the four main research themes [37].

In September 2016, the University of Waterloo, Canada, announced it will receive a further CA$76.3 million through the Canada First Research Excellence Fund [38]. At the same time in Australia, the ARC Centre of Excellence for Quantum Computation and Communication Technology (CQC2T) was awarded AU$33.7 million [39]; and the University of Queensland's Centre for Engineered Quantum Systems (EQuS) received AU$31.9 million over seven years [40].

The pace of research is accelerating with several important breakthroughs already achieved. For example, A 2 qubit gate is one of the fundamental operations for quantum computing. Currently, **Ion-based** qubits show the highest accuracy (also called 'fidelity') for such operation. The current record of the lowest 2 qubit gate error is ~0.1% [41, 42]. In the meantime, University of Oxford has demonstrated the first 'hybrid' entanglement between two trapped-ion qubits held in different isotopes of calcium [43]. Other breakthroughs include near [44] and far-field [45] microwave addressing methods to drive ion-based technology to lower cost.

The **superconducting** qubit landscape has attracted substantial commercial research interest. Both Google and IBM have published results in this area. In March 2015, Google demonstrated a linear array of nine qubits in operation [46].

Solid-state spin qubits have also made significant breakthroughs in the last decade. In October 2015, Veldhorst et al. demonstrated the first qubit gate operation on a heavily enriched Silicon platform [47]. In 2015, Henson et al. demonstrated entangled single NV qubits separated by more than 1 km using entangled photons [48]. This demonstration is an important step towards linking several modular diamond based quantum modules together.

This global research effort has led to a substantial number of journal publications in the field of Quantum Computing. Table 4.1 and Table 4.2 show a list of Universities and research institutes ranked by their number of publications in quantum computing and quantum information processing respectively. These results are compiled from a Web of Science search. Their search metrics can be found in the captions below.

Table 4.1 Rankings by organisation from Web of Science (https://apps.webofknowledge.com/) search results for keywords: "quantum comput*" in the TITLE field only, and across all journals from 2006–July 2016

Rank	Organisation	Publications
1	University of Oxford	65
2	National University of Singapore	62
3	University of Waterloo	52
4	Chinese Academy of Sciences	45
5	University of Queensland	42
6	CNRS	42
7	University of Maryland	39
8	University of Cambridge	37
9	Max Planck Institute	34
10	University of Science and Technology of China	32
11	Harvard University	30
12	University of Tokyo	30
13	University of California Santa Barbara	27
14	Stanford University	24
15	MIT	23
16	RIKEN	21
17	CNR	17
18	Berkeley	12
19	Japan Science & Technology Agency	12
20	ETH	8
21	Delft University	6
22	SLAC National Accelerator Lab	0

Table 4.2: Rankings by organisation from Web of Science (https://apps.webofknowledge.com/) search results for keywords: "information processing" AND "quantum" in the TITLE field only, and across all journals from 2006–July 2016

Rank	Organisation	Publications
1	Stanford University	18
2	University of Tokyo	14
2	Chinese Academy of Sciences	14
4	RIKEN	9
5	University of Oxford	7
5	University of Science and Technology of China	7
5	University of Queensland	7
5	CNRS	7
5	University of Waterloo	7
10	MIT	6
10	Max Planck	6
10	University of Cambridge	6
13	Harvard University	4
14	University of Maryland	3
14	Berkeley	3
14	ETH	3
17	University of California Santa Barbara	2
17	National University of Singapore	2
17	CNR	2
17	Japan Science & Technology Agency	2
21	Delft University	0
21	SLAC National Accelerator Lab	0

5: Public Perceptions

Quantum computing is a disruptive technology that brings the promise of changing the world, and with that comes a degree of mystery and hype.

Quantum computing is no longer limited to scientific journals and has entered the mainstream media, encompassing news sites, technology publications, popular science and social media. A cursory search on YouTube on ‘quantum computing’ returned over a half a million results!

Media coverage is on the whole largely positive, reporting technological advancements and potential benefits. For example, an article in The Guardian in May 2016, asked: *“Has the age of quantum computing arrived?”* [49].

In August 2016, Wired magazine reported that *“Engineers just created a programmable quantum computer”*, describing the major advance in programming a 5-qubit quantum computer based on Ion Trap technology [50]. Also in August 2016, TechRadar, an online technology publication, informed its readers that *“Quantum computers just took a huge logical leap forward”*, where researchers at Oxford University set a new record in developing a quantum logic gate with 99.9% precision [51]. That level of precision is required for quantum computers to operate.

Quantum computing does face some challenges in perception. It’s a difficult subject to explain to a wide audience, and there are concerns over its impact from breaking existing encryption schemes to being a tool for tyranny.

We discuss some of the challenges below and put the fears into context.

5.1 Quantum Confusion

The basic operating principles of a Quantum Computer use a branch of physics known as Quantum Mechanics. It is the science of the very small, the interaction of energy with atoms and subatomic particles, the fundamental building blocks of the universe.

At the incredibly small scale at which the components of a quantum computer operate, a particle exhibits behaviours that are baffling and in contradiction with our daily experience. For example, a particle’s position and velocity cannot be measured at the same time (known as the **uncertainty principle**). A particle may pass through a barrier instead of being stopped by it (**quantum tunnelling**). A particle may be in more than one state at the same time (**quantum superposition**). See §"1.1 Quantum Computing – from the unthinkable to the inevitable" for an overview of superposition and entanglement.

Trying to explain these phenomena in a simple way to a non-scientific audience isn’t easy. Words such as *strange*, *bizarre*, *weird*, *spooky* or *magic* are employed for the task. **Schrödinger’s cat** is brought out in a box to help explain quantum superposition, and one online article invokes *Alice in Wonderland* to sum up the world of quantum physics [52].

Against this backdrop, quantum computing is perceived as mysterious and impenetrable. One author writing for Scientific American wrote:

> *"The word quantum imbues any topic with instant mystique. Unfortunately, it often doubles as a 'keep out' sign – a signal that an impenetrable quagmire of math and physics awaits anyone foolish enough to peer behind the label"* [53]

More effective strategies for communicating these complex ideas are required, perhaps with the aid of people from non-scientific backgrounds.

Justin Trudeau, the Canadian Prime Minister, explained the principles and importance of quantum computing during a press conference in April, 2016. The news subsequently went viral on social media [54].

5.2 Unrealistic Expectations about Quantum Computing

In April 2012, Scott Aaronson, Associate Professor of Electrical Engineering and Computer Science at the Massachusetts Institute of Technology (MIT), featured in a BBC News article entitled *"Quantum computing: Is it possible, and should you care?"* [55]

Aaronson said:

> *"The journalists have to sell everything, so they present each thing like we're really on the verge of a quantum computer – but it's just another step in what is a large and very difficult research effort."*

Quantum computing is an exciting technology but over-hyping research outputs will only damage public confidence. One solution to this is more public engagement by the researchers themselves. For example, in October 2015, Jerry Chow, Manager of the Experimental Quantum Computing group at IBM Research, gave a talk at the TED Institute on *"The future of supercomputers? A quantum chip colder than outer space"* [56].

Another issue is trust in the product. D-Wave encountered heavy scepticism when their first quantum computer was announced, spawning articles like "D-Wave's Quantum Computer Courts Controversy" [57], "Is D-Wave's quantum computer actually a quantum computer?" [58], and "D-Wave's Year of Computing Dangerously" [59].

There was genuine concern that the D-Wave product was not a true quantum computer but masquerading as one. It is now largely accepted that the D-Wave is a type of quantum computer, albeit limited in the range of problems it can solve. D-Wave's customers include Lockheed Martin, Google (now Alphabet Inc.), NASA and the Los Alamos National Laboratory.

5.3 Breaking Encryption

Many activities over the Internet are secured by encryption, such as messaging, online shopping, banking and social media.

One encryption scheme is called 'RSA' and has been successfully used for 40 years. The scheme uses a pair of keys (public and private) to scramble or unscramble data. The longer the key size, the more secure it is. For example, the digital certificates used to secure Internet websites have a key size of 2048 bits.

Trust in encryption schemes relies on the fact that trying to unscramble a message can take a very long time, on the order of millions to billions of years! This is due to the sheer number of combinations to try in order to find the key.

For example, there are 2^{112} (**5,192,296,858,534,827,628,530,496,329,220,096**) combinations to break our RSA key of 2048 bits.

The ability of quantum computers to solve problems that can take millennia on conventional computers means that encryption schemes can be potentially broken very quickly (minutes, hours or days). This is very worrying as a BBC article in August 2014 pointed out: *"Do quantum computers threaten global encryption systems?"* [60].

The quantum computer that can achieve this feat hasn't been built yet, and will require on the order of 10 million qubits [61]. By that time new encryption schemes will be in place that are resistant even to quantum computers. This is termed **post quantum cryptography** and Google is already implementing it.

In July 2016, Google announced it was testing post quantum cryptography on the 'Chrome Canary' web browser, using an algorithm they have termed 'New Hope' [62].

Engaging with industry at a Quantum Technology Showcase event / *EPSRC, Dan Tsantilis*

5.4 Responsible Innovation

Quantum computing is a powerful technology that has the potential to benefit humanity in many ways, such as discovering life-saving drugs, more accurate weather forecasting, useful new materials (e.g. high efficiency solar cells), and validating complex software (e.g. flight management systems). We can also imagine the cities of the future guiding driverless cars in real-time, choosing the most optimal route from A to B, with a network of quantum computers.

Quantum computing also brings concerns over breaking encryption (see § "5.3 Breaking Encryption"), spying, artificial intelligence, and the slow pace of regulation in the face of fast moving technology [63].

While we do not know how quantum computers will be used by governments and multinational corporations, the future hasn't happened yet. There is time to discuss and debate the many issues arising from this new technology.

In the UK, the Engineering and Physical Sciences Research Council (EPSRC) has established a 'Framework for Responsible Innovation' [64]. The Networked Quantum Information Technologies (NQIT) initiative led by the University of Oxford, has a specific work package dedicated to this called 'Responsible Research and Innovation' (RRI).

RRI activities include engaging with industry and the general public to present quantum computing and stimulate discussion. These dialogues facilitate exchange of knowledge and ideas, and are expected to impact upon government policy.

6: Potential Market Segments

Media Market Research have projected the quantum computing market to exceed **USD 5 billion** by 2020 [8]

Quantum computing is a geopolitical and economic game changer. It will potentially impact across every area of our lives, create new industries and disrupt existing ones. Some of the potential market segments are discussed below.

6.1 Health

The global healthcare market is estimated to be worth USD $8 trillion [65].

Quantum computing is expected to bring the following benefits: accelerate research into diseases such as cancer, find new drugs and pioneer new treatment regimes.

Combating Cancer

Cancer is a leading cause of death worldwide. The World Health Organisation expects annual cases to rise from 14 million in 2012 to 22 million over the next two decades [66].

Understanding cancers and finding treatments is a subject of ongoing research. The following extract from the Times Colonist Editorial on *'Finding tools to defeat cancer'* puts the task into context:

> *"It took 13 years to map the 20,000 genes in the human genome. To map every mutation in the 50 most common cancers would be 10,000 times more complex… And many of the chemotherapy drugs in use today were discovered 50 or more years ago. They are the bluntest of instruments, killing indiscriminately any cell that grows faster than normal."* [67]

Quantum computing is expected to bring the following benefits in the long term [68]:

1. Accelerate research into cancer and drug discovery.
2. Improve radiotherapy treatments by calculating the correct dosage and area of exposure to minimise side effects.
3. Revolutionise oncology through individually tailored treatments.

Protein folding

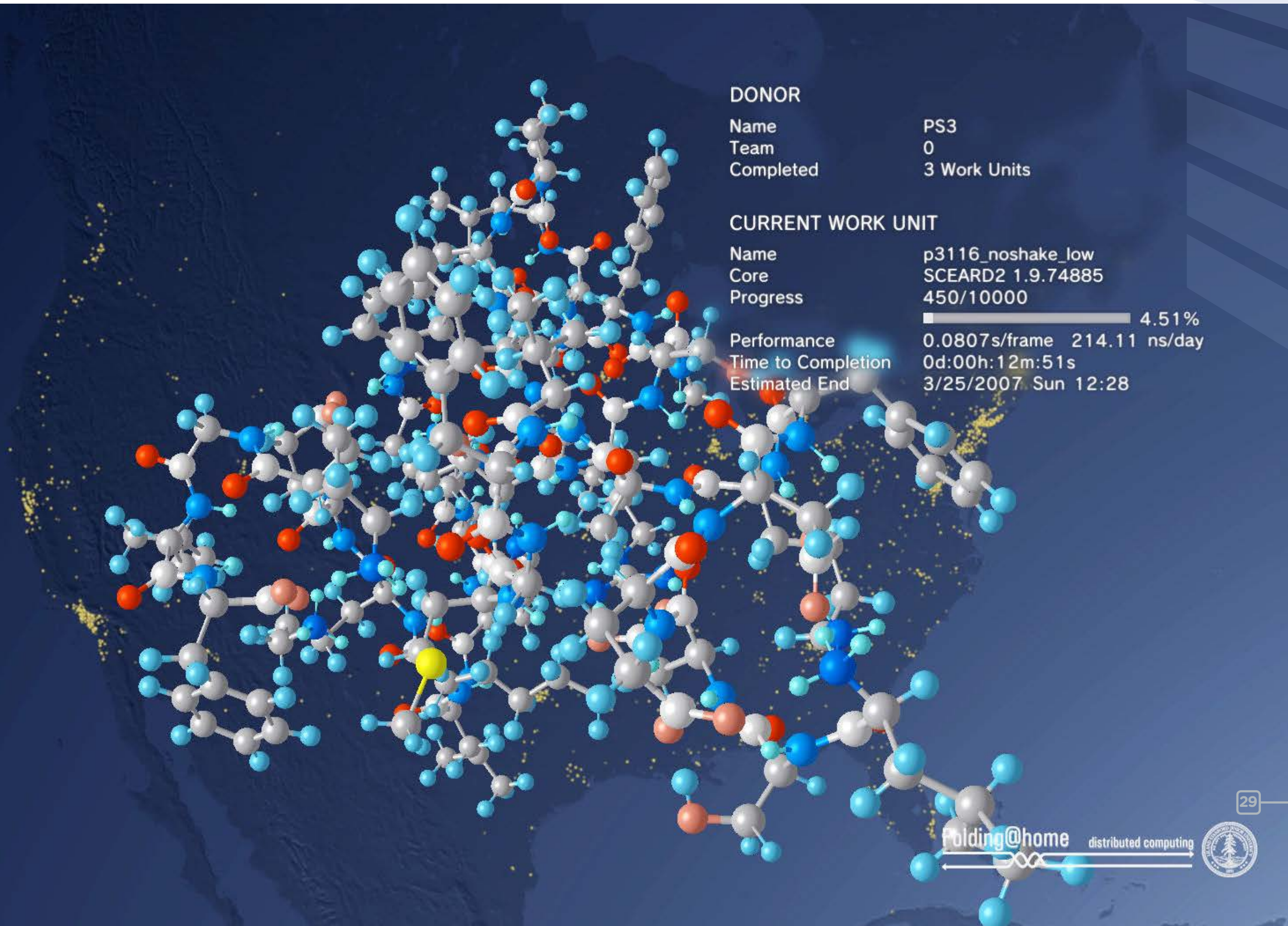
Understanding the structure of proteins and how they fold is crucial to developing treatments for misfolded-protein diseases such as Alzheimer's, Huntington's, Parkinson's disease and many cancers.

To simulate protein folding is computationally expensive in terms of time and cost, requiring access to supercomputing facilities. As supercomputing resources are shared by many other researchers, research bottlenecks are created.

The "Folding@home" project from Stanford University [69] takes an innovative approach, creating the world's largest distributed supercomputer. This project relies on volunteers to download special software that runs when their computers aren't busy. At the time of writing, 87,000 computers around the world are outputting 85,000 teraflops of computing power!

Quantum computers are expected to make a huge impact in speeding up these calculations over and above the performance of current supercomputers.

In 2012, a team of researchers at Harvard University, led by Professor Alan Aspuru-Guzik, conducted 6 experiments (up to 81 qubits) to apply quantum annealing to lattice protein folding problems using a D-Wave One quantum computer [70]. It was the first time that this technique had been used in the field of biophysics.



Visualisation of the Folding@Home protein simulation on "Playstation's Life with Playstation"
http://www.yespleasestudio.co.za/foldinghome-distributed-computing/

6.2 Finance

The global market for financial assets (stocks, bonds, securities) is estimated to be $294 trillion, which includes the $69 trillion stock market [71].

Some problems in Finance are very difficult to solve with current technology, and can take years of computing time. These include:

1. Dynamic portfolio optimisation.
2. Risk management and regression analysis.
3. Scenario analysis.
4. Quantitative analysis.
5. Option pricing for complex derivatives (which are path dependent). Computing different paths is time consuming and expensive.

For example, consider the case of an asset manager who has to rebalance their portfolio to maintain a level of desired asset allocation. Every time this is done, their investors lose money through various costs, termed 'slippage'. Losing 3% on rebalancing costs has been described as *"a death by a thousand cuts"* [72].

In addition, such assets are targeted by high frequency algorithmic trading, which can lead to market chaos. An example of this was the 'Flash Crash' in 2010, where the Dow Jones Index plunged 9% in 20 minutes [73].

With the computational power of quantum computers, the asset manager can decide when to rebalance their portfolio and do this activity less frequently. This has the effect of reducing the impact of high frequency trading on those assets.

D-Wave and quantum software firm, 1QBit, have teamed up with financial industry experts to create an online community for quantitative analysts, called *"Quantum for Quants"* 26 [29]. This initiative, launched in May 2016, is to encourage discussion, collaboration, and provide tools and resources for quantum computing.

6.3 Machine Learning

The purpose of machine learning is to give computers the ability to learn without being explicitly programmed.

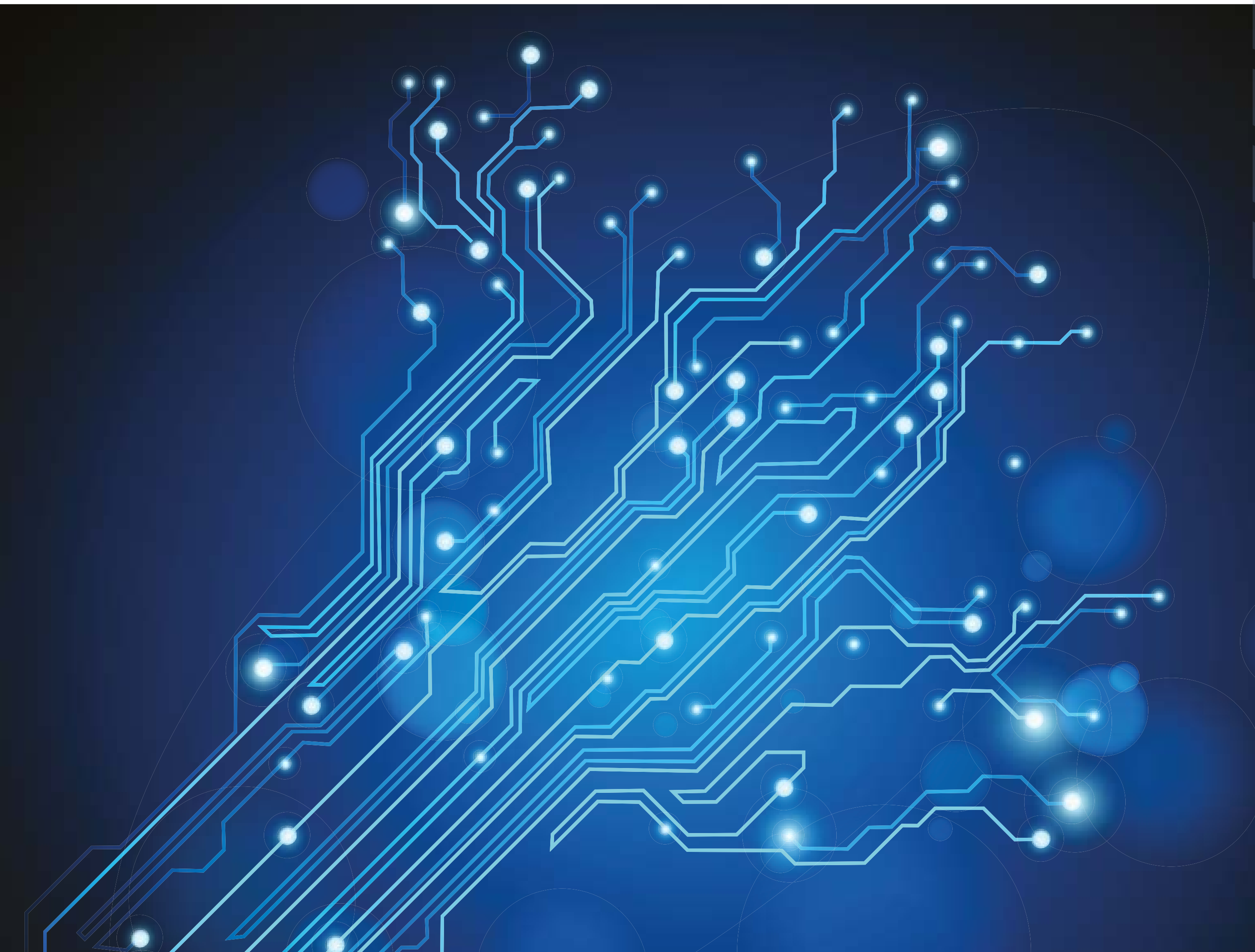
Machine learning is already an increasing feature of our lives even if we are not aware of it. Everyday applications include email filtering, text, speech and facial recognition, targeted advertising and goods (based on viewing or purchase history). More complex examples include artificial intelligence (AI), advanced robotics and driverless cars.

Quantum machine learning is in its infancy, but ongoing research in algorithm development using the D-Wave quantum computer has already yielded promising results [74,75].

These include:

1. Very compact and efficient recognisers for low power devices (such as mobiles).
2. Handling highly polluted training data, where a high percentage of the examples are mislabelled. This is very useful for dealing with real-world data.
3. Recognising objects in images. For example, Google researchers working with D-Wave created a system to answer the question: *“Is there a car in this picture?”* Over 500,000 optimisation problems were solved during the learning phase.
4. Automatic labelling of news stories and images into categories.
5. Efficient video compression.

Another example of machine learning is optical character recognition. In 2014, a Chinese research team from the University of Science and Technology of China successfully demonstrated optical character recognition using a 4-qubit quantum processor (based on Nuclear Magnetic Resonance (NMR) technology). The aim of their experiment was to recognise the numbers ‘6’ and ‘9’ written in different handwriting, styles and fonts [76].



6.4 Simulation

Simulating molecules

The global market for chemicals is estimated to be worth USD 3 trillion, and a number of firms, including Microsoft, have made simulating molecules on a quantum computer as a priority area of research [77].

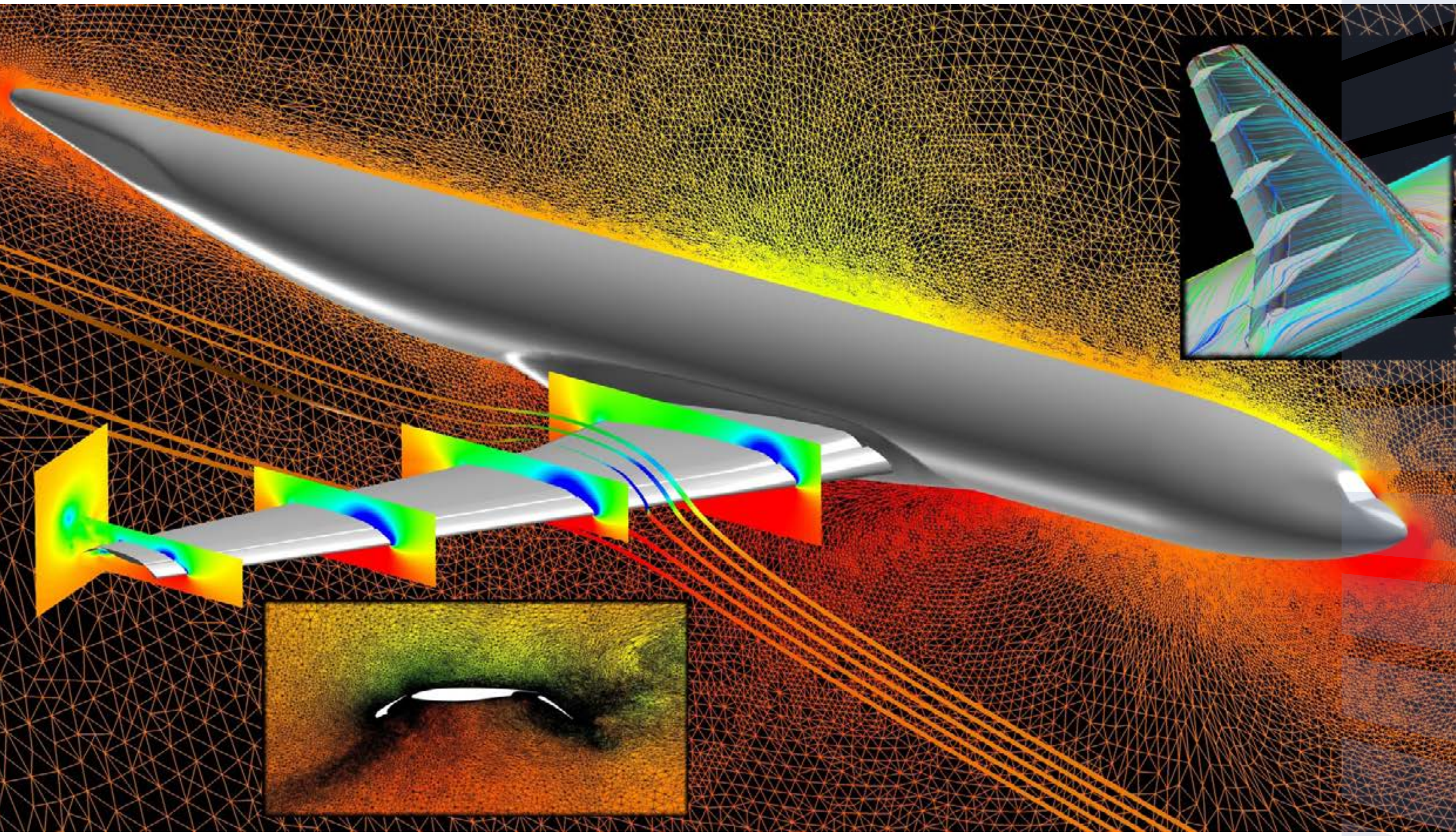
In July 2016, Google announced it had made an important breakthrough by simulating the Hydrogen molecule for the first time using a scalable quantum device (VQE - Variational Quantum Eigensolver, using superconducting qubits) [78].

This is significant because they enable numerically exact prediction of chemical reaction rates, which will advance understanding of chemistry. A conventional computer can also do the modelling but computation times scale up quickly. For example, it takes a supercomputer about 10 days to calculate the energies for propane (C_3H_8).

There are numerous applications in chemistry, for example, making better batteries, finding a better catalyst for carbon sequestration, or producing fertilisers using less intensive methods.

A key ingredient in the manufacture of fertilisers is ammonia, which is produced using the intensive 'Haber Process'. About 450 million tons of fertiliser is made annually, consuming 2% of the world's energy [79]. If ammonia can be produced more efficiently, it will save costs, bring benefits to the environment, while supporting a growing population.

Professor Matthias Troyer at the Institute for Theoretical Physics at ETH Zurich has been looking at problems that would benefit from quantum computing. One example is the production of ammonia, a key ingredient in the manufacture of fertilisers produced using the intensive 'Haber Process'. About 450 million tons of fertiliser is made annually, consuming 2% of the world's energy [79]. Troyer believes that a quantum computer could help design a much more efficient catalyst that will save costs, bring benefits to the environment, while supporting a growing population. "That would be worth building a quantum computer for," said Troyer [80].



A computational fluid dynamics (CFD) visualization produced using a NASA supercomputer, showing a mesh adaptation used to simulate a transport aircraft
NASA / Elizabeth Lee-Rausch, Michael Park
http://www.nasa.gov/aero/aeronautical-simulation.html

Aeroplane wing design

It currently takes several years for engineers to test the design of an aeroplane wing, and model airflow at different angles and speeds. A good design will reduce operating costs, save fuel, which in turn means less carbon emissions [81].

For example, NASA announced a longer, thinner wing design that cuts fuel costs in half [82].

Quantum computers can potentially reduce this process to weeks or months instead of years.

6.5 Logistics

The global market for logistics is estimated to be over \$4 trillion, with road freight accounting for \$2 trillion [83].

For a courier company making deliveries, working out the most efficient routes at different times of day can be a complex task. If the driver is stuck in traffic there is an immediate impact on the schedule. The company has to take action to minimise knock on consequences, while keeping customers happy.

Suppose our driver has to cover for a sick colleague, and has to make deliveries to 4 cities instead of 3. Working out the most efficient route is manageable. However, this problem quickly scales as you add more cities. For example, visiting 10 cities has over 180,000 combinations. Increasing to 15 results in the order of 10^{10} combinations!

This is known as the 'Vehicle Routing Problem' (VRP), and benefits with the computing power and speed-up that quantum computing promises.

Researchers at Manchester Metropolitan University have developed a quantum annealing algorithm for tackling VRP, working with IT technology company ServicePower Technologies PLC, a software provider for logistics firms.

In March 2016, ServicePower's Chief Executive, Marne Martin said:

> *"Quantum annealing is expected to take our scheduling products to the next level, providing the highest in cost reduction to our clients and improving their abilities to provide exceptional services to their own customers."*

ServicePower has made 3 patent applications covering this work [84].

6.6 Software Verification & Validation

Creating highly complex systems such as aircraft, reusable space rockets, or an aircraft carrier requires an enormous amount of effort to verify and validate that every system operates correctly.

Lockheed Martin is an advanced technologies company, producing elaborate systems for aerospace, defence, space, energy and emerging technologies sectors. Half the costs on creating these solutions is spent on verification and validation [85].

Lockheed Martin turned to D-Wave to see if quantum computing could help identify errors faster. They supplied D-Wave with a sample of a 30-year-old software code from the F-16 jet aircraft. It had taken Lockheed Martin 6 months to find the error, D-Wave found it in 6 weeks.

Dr Ray Johnson, then Chief Technology Officer at Lockheed Martin, now Executive Director at QxBranch, said:

> *"We purchased the D-Wave machine to address the issue of software complexity by using the D-Wave to rapidly evaluate all possible conditions in the code."* [86]

Another company investigating quantum computing for verification and validation is Airbus [87], but complexity in software is not limited to the aerospace industry.

The Ford GT car has 10 million lines of software code, which is 3 million more than the Boeing 787 Dreamliner [88]. The Windows operating system is on the order of 50 million lines of code, while Google's repository stretches to 2 billion [89].

The cost of software glitches can be high. For example, in 2014 car manufacturer Toyota recalled 1.9 million Prius cars globally due to a software error in the hybrid system [90]. In June 2016, another car manufacturer, Fiat, recalled 16,000 Fiat 500e electric cars due to a software fault that would shut down the power in certain situations [91].

Quantum computers will allow companies to test their software more thoroughly before customers are affected, saving a fortune in recall costs, preventing lawsuits and public relations disasters.

Appendix

Commercial Investment Timeline

The quantum computing timeline showing commercial investment and major milestones is shown in the tables below from years 1999–2009, 2011–2013, 2014–2015 and July 2016.

Quantum computing commercial investments and milestones 1999–2009	
1999	D-Wave founded and the first investment of CAN $4,059.50 [2]
2006	D-Wave receives $14m in Series B funding from: GrowthWorks Capital, BC Investment Management Corporation, Draper Fisher Jurvetson (DFJ), BDC Venture Capital, Harris & Harris Group [92]
	Microsoft establishes “Station Q” research group at the University of California, Santa Barbara, to research ‘topological quantum computing’ [93]
2007	D-Wave’s “Orion” quantum computer (16 qubit) debuts [94]
	Orion Quantum Computer demonstration in solving Suduko puzzles [95]
	BBN technologies (now Raytheon BBN) wins $3.5m contract from the Defense Advanced Research Projects Agency (DARPA) for the military applications of quantum information science. [96]
2008	D-Wave raises $17m in Series C funding from: Draper Fisher Jurvetson (DFJ), Harris & Harris Group, GrowthWorks Capital, BDC Venture Capital, International Investment & Underwriting Limited, PenderFund Capital Management, BC Investment Management Corporation [97]
2009	Google demonstrates quantum computer image search using D-Wave processor at the Neural Information Processing Systems (NIPS) conference [98]

Quantum computing commercial investments and milestones 2011-2013	
2011	D-Wave announces "D-Wave One" quantum computer (128 qubits) [99]
	Lockheed Martin buys first D-Wave One quantum computing system [100]
2012	1QBit founded, first company dedicated to quantum software [101]
	D-Wave announces 512 qubit quantum computing chip codenamed 'Vesuvius' [102].
	D-Wave raises $3.02m debt financing [103]
	In-Q-Tel invests $1.2m in D-Wave [104]
	D-Wave raises additional $30m from: GrowthWorks Capital, Harris & Harris Group, International Investment & Underwriting Limited, Kensington Capital Partners Limited, In-Q-Tel, Business Development Bank of Canada, Draper Fisher Jurvetson (DFJ), Goldman Sachs, Bezos Expeditions, British Columbia Discovery Fund [105]
	Harvard presents results of the largest folding protein problem solved using a D-Wave [106].
	Raytheon BBN awarded $2.2m by Intelligence Advanced Research Projects Activity (IARPA) to research quantum computing [107].
	Qubitekk founded [108]
2013	D-Wave raises £1.01m in undisclosed funding [109]
	Google, NASA and Universities Space Research Association (USRA) purchase D-Wave Two and install it at NASA's Quantum Artificial Intelligence Lab [110]
	Lockheed Martin upgrades to the D-Wave Two [111].
	Rigetti Computing founded by ex-IBM researcher, Chad Rigetti [112]. Start-up has ambitions to build a solid state quantum computer chip with a 40 qubit chip by 2017.
	Quantum Valley Investments founded [113]. BlackBerry co-founders Mike Lazaridis and Doug Fregin establish a $100-million fund for quantum computing.
	Qubitekk receives undisclosed seed funding [114]
	Qubitekk receives $95k grant from the US Department of Energy [115]

Quantum computing commercial investments and milestones 2014-2015	
2014	CME Group invests in 1Qbit – Series A funding (undisclosed) [116]
	Cambridge Quantum Computing Ltd incorporated at Companies House, UK [117]
	Commonwealth Bank Australia (CBA) invests AUD $5m in the centre for quantum computation and communication technology at the University of New South Wales (UNSW) [118].
	D-Wave raises $3.86m in undisclosed funding [119]
	D-Wave raises $28.36m from: Goldman Sachs, Draper Fisher Jurvetson (DFJ), Business Development Bank of Canada [120]
	D-Wave raises additional $2.19m in undisclosed venture capital [121]
	IBM announces $3b initiative to push the limits of chip technology and includes quantum computing [122].
	Rigetti Computing raises $2.5m seed funding from 18 investors: AME Cloud Ventures, Morado Venture Partners, Susa Ventures, Tim Draper, Y Combinator, Fenox Venture Capital, Farzad (Zod) Nazem, Felicis Ventures, Streamlined Ventures, Berggruen Holdings, Alchemist Accelerator, Data Collective, Charlie Songhurst, Taryn Naidu, Ian McNish, Paul Buchheit, Erick Miller, David Beyer [123]
	Rigetti Computing raises additional $500k convertible note from Streamlined Ventures [124].
	Qubitekk receives $3m grant from US Department of Energy [125]
	Qubitekk presents keyless authentication method using quantum cryptography at IQC/ETSI workshop [126].
	Anyon Systems Inc founded. Canadian technology startup providing toolkits for design and optimization of nano/quantum electronics [127]
2015	1QBit receives Technology Pioneer Award from World Economic Forum [128]
	Alibaba Cloud (Aliyun) and the Chinese Academy of Sciences sign a memorandum of understanding to co-found the Alibaba Quantum Computing Laboratory [129].
	Alibaba pledges to invest 30m Yuan (approx. $4.5m) annually into quantum computing [130]
	Cambridge Quantum Computing Ltd (CQCL) receives $50m funding over 3 years from Grupo Arcano [131].
	CQCL announces “t|ket>”, a quantum computing operating system [132].
	Commonwealth Bank Australia (CBA) pledges extra AUD $10m in UNSW for quantum computing research [133].
	Telstra matches CBA and invests AUD $10m in UNSW [134].
	D-Wave raises $29m in undisclosed funding [135].
	D-Wave announces next generation D-Wave 2X quantum computer (1000+ qubits) [136].
	Los Alamos National Laboratory buys a D-Wave 2X quantum computer [137]
	Google and NASA upgrade to D-Wave 2X and extend contract with D-Wave for 7 years [138]
	Google developing its own quantum annealing chip with 100 qubits by 2017 [139]
	IBM makes important milestone towards reliable quantum processors with new error detection method [140]
	IBM awarded IARPA grant (undisclosed) to advance research towards a universal quantum computer [141]
	Intel CEO, Brian Krzanich writes article entitled “The Promise of Quantum Computing” [12].
	Intel to invest $50m over the next 10 years and partners with Delft University of Technology, Netherlands, and TNO (the Dutch Organization for Applied Scientific Research) [142].
	USC-Lockheed Martin Quantum Computing Centre to be upgraded to the D-Wave 2X [143].
	Microsoft releases “LIQUi|>”, a free software simulation toolkit for quantum computing [144].
	Qubitekk announces “QES1”, a quantum entanglement source for scientists [145].

Quantum computing commercial investments and milestones to December 2016	
To Dec 2016	1QBit and D-Wave partner with financial industry experts to launch "Quantum for Quants" online community [29, 30].
	Alibaba Cloud and Nvidia to invest $1b in cloud and quantum computing [146]
	Atos CEO Thierry Breton discusses quantum computer project in interview with Les Echos [147].
	Bloomberg names CQCL as one of the breakthrough businesses of 2016 [148]
	D-Wave CEO, Vern Brownell, says "We're at the dawn of this quantum computing age" [13]
	Harris & Harris Group has partnered with TriPoint Global Equities, and its online platform BANQ, to enable accredited investors to co-invest on next round of D-Wave funding ($15million) [4]
	Google announces digitized adiabatic quantum computing with a superconducting circuit. This is an important step towards a universal quantum computer [149].
	Google tests post-quantum cryptography on Chrome Canary web browser. This is to counter the threat from quantum computers [62].
	Google's quantum computer simulates energy of a hydrogen molecule. This work was in collaboration with Harvard University, Lawrence Berkeley National Labs, UC Santa Barbara, Tufts University, and University College London [150].
	IBM makes quantum computing accessible to the public through the "IBM Quantum Experience" web portal. The portal gives access to a 5 qubit quantum computer [151].
	Playground Global, an investment firm and incubator overseeing USD 300 million, invests in unnamed quantum computing startup [10].
	Peter Lee, the corporate vice president of Microsoft Research says: *"Quantum computing is stupendously exciting right now. At least at my part of Microsoft Research, it's the largest area of investment, and we just have the sense that we're on the verge of major scientific achievements"* [11]
	Purdue University. Microsoft 'Station Q' establishes "Station Q Purdue" and invests a multi-million amount (undisclosed) for research [152].
	Microsoft announces winners of their Quantum Challenge, using their Liqui|> toolkit, with a $5000 prize [153].
	Rigetti Computing testing 3 qubit chip (aluminium circuits on a silicon wafer) [154].
	Quantum Valley Investments: Mike Lazaridis gives keynote speech at the Quantum Europe 2016 Conference in Amsterdam [155]
	H-Bar Quantum Consultants founded [156]
	Sparrow Quantum founded to produce single photon source chip [157]
	QC Ware receives undisclosed seed funding from Airbus Ventures and the D. E. Shaw group [158]
	D-Wave raises US$21 million from Fidelity Investments and PSP Investments [159]
	D-Wave Government Inc. subsidiary established in Washington to focus on the U.S. Government [160]
	Atos launches "Atos Quantum", quantum computing initiative in Europe [27]
	Microsoft hires: Professor Leo Kouwenhoven (Delft University, founding director of QuTech), Professor Charles Marcus (Niels Bohr Institute, Director of the Danish National Research Foundation-sponsored Center for Quantum Devices). Professor Matthias Troyer (ETH Zurich) and Professor David Reilly (director of the Centre for Quantum Machines at the University of Sydney in Australia) may also be added to the team [161]
	Microsoft and QuTech connected for 10 years in unspecified investment [162]

Open Source Software

The table below lists some popular open source software applications with market share figures if available.

While not pertinent to quantum computing directly, it is interesting to see how much open source software is used, and this could apply one day to open source quantum computing applications.

Software		Description
	Chromium	The Chrome web browser by Google is based on Chromium and has 59.5% market share in July 2016 [163].
	Linux	Operating system with 2% market share in July 2016 [164].
	MySQL	Relational Database, ranked second after Oracle in popularity in July 2016 [165].
	Apache HTTP Server	Web server with 43% market share of the top million busiest websites for July 2016 [166].
	WordPress	Content management system (CMS) with over 59% market share of all websites using a CMS in 2016 [167].
	Python	Python computer language ranked third most popular of 2016 according to IEEE Spectrum [168].
	LibreOffice	Alternative to Microsoft Office
	GIMP	Alternative to Adobe Photoshop for image editing
	Audacity	Audio software for multi-track recording and editing

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