Practical Quantum Computing: A Patent Landscape Report

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• Headlines

- Patenting in the field of Quantum Computing (QC) has exploded over the last three years.
  - QC patent family publications are projected to increase by 430% between 2014 and 2017.

- The most talked about companies in the field are D-Wave Systems, IBM, Microsoft, Google, and Intel, but Google and Intel have much smaller portfolios that the other three companies, and could be interested in acquisitions.

- IBM is building an enormous portfolio in the QC space, primarily in Qubit Technologies, and Hardware, and have had the most patent families published in the last two years.

- Northrup Grumman, and HP are two American companies who also have substantial patent portfolios in the QC space, and might make excellent partners, or patent acquisition targets as consolidation begins when the market grows.

- Nokia/Alcatel, NEC, and Honeywell are also companies that have published, or are projected to publish a larger than average number of patent families in QC over the past two years.

• Headlines

- While American companies are often discussed as leaders in the QC field, there are a number of Japanese companies that have also invested heavily in QC including NTT, Hitachi, Toshiba, Fujitsu, and Sony.
- Chinese organizations are patenting at an accelerated rate, and they are primarily interested in cryptology.
- University backed start-ups are a significant source of potentially valuable patents, and portfolios. MIT, Yale, Harvard, and Stanford portfolios, or start-ups associated with them will be likely acquisition targets as the market grows, and larger players are looking to solidify their positions.
- Other smaller companies to consider for partnerships, or patent acquisition opportunities include: Quantum Circuits (Yale driven start-up), Magiq Technologies, Qucor, Element 6, Rigetti Computing, and 1QB Information Technologies.

• Executive Summary

- Patenting in the field of Quantum Computing (QC) has exploded over the last few years
  - QC patent family publications are projected to increase by 430% between 2014 and 2017

- This exponential growth can be equally attributed to patent publications in the Qubit Technology, and Hardware categories

- Within the Qubit Technology category the explosive growth is being driven by patenting in the Super Conducting Loop method of generating qubits for QC
  - Quantum Dot methods are also projected to see significant growth in 2017

- Within the Hardware category patenting growth is coming primarily from quantum circuits, and generic quantum hardware applications
  - Patent publications in logic gates and photon technologies are also projected to see growth in 2017

- The majority of the QC innovations are coming from the United States, but Chinese patent publication are rapidly increasing
  - Japan traditionally had the second largest collection of QC patent families, but China surpassed them in 2014

Executive Summary

- D-Wave Systems has the largest collection of patent families associated with QC, and it is projected to grow significantly in 2017
  - IBM has the second largest portfolio, but is projected to have almost twice as many family publications in 2017 than D-Wave Systems
  - Microsoft, NTT, and Northrop Grumman round out the top five corporate assignees
  - HP comes in at number seven in count of patent families, but they look to be scaling back their patent filings
  - Nokia/Alcatel, Honeywell, and Google standout among the top companies with a large increase in family publications since 2016

- Besides IBM, D-Wave Systems, Nokia/Alcatel, Honeywell, and Google, Microsoft, Northrup Grumman, NTT, Hitachi, Toshiba, and Boeing comprise the list of companies with the highest number of patent family publication since 2016

- Generally speaking, the top American companies are primarily focused on Qubit Technologies, and Hardware, and less on Applications compared to the Japanese companies who are mainly focused on Hardware components
  - D-Wave is an exception with more families associated with Applications than Hardware
  - Considering Qubit Technologies IBM has the most diversified portfolio, but the highest interest in Superconducting qubits. D-Wave and Google are also interested in this area while Microsoft is betting on Topological qubits

Executive Summary

- When the major Japanese companies file on Qubit Technologies they are more likely to be interested in Quantum dot qubits, followed by Superconducting qubits

- Many of the top Japanese patent families are related to general quantum hardware and devices, which differs from the top U.S. firms who are more focused on individual components like circuits, logic gates and manufacturing techniques from a hardware perspective

- Intel is another major corporation that is heavily invested in quantum computing, but they are not very active from a patenting perspective as they have just five patent families
  - They do however cite a significant number of patent families found in this study in their patents related to tangential technologies

- A company interested in competing with IBM should have a closer look at the Northrup Grumman portfolio
  - While significantly smaller than IBM the Northrup portfolio covers some of the same areas

• Executive Summary

- Some smaller companies that emerged as potentially interesting in this study include: Quantum Circuits (Yale driven start-up), Magiq Technologies, Qucor, Element 6, Rigetti Computing, and 1QB Information Technologies

- MIT is currently very active in quantum computing from a patenting perspective, having five applications published through the first six months of 2017
  - Other recently active Western Universities include Harvard, Yale, WARF, New South Wales, Oxford and Univ. of Michigan
  - Stanford, and Univ. of California also have reasonably sized portfolio, that are cited frequently, and are a little older

- Chinese Universities make up six of the top 13 positions when looking at the largest number of patent family publications over the last two years, and more than half of the total number of University patent families in that period

- The following companies score well when looking at their forward citations considering their portfolio and family size, and average age: Northrup Grumman, HP, Hitachi, Fujitsu, Sony, Mitsubishi, Magiq, Qucor, Element Six, MIT, and Harvard

- US Government labs patent most frequently in the QC space followed by Japan, which has not published recently, and China who is projected to have as many publications as the US in 2017

INTRODUCTION TO PRACTICAL QUANTUM COMPUTERS

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Introduction to Practical Quantum Computing

- The concept of quantum computing has been around, at least from a theoretical perspective, since the 1980's when Nobel prize-winning physicist Richard Feynman first spoke about the idea. Initially it was thought to be an impossible technology to harness due to the unstable nature of particles on the quantum scale, however due to technological advancements throughout the 1990's and 2000's not only has quantum computing become possible but it has transformed into one of the fastest growing industries in computer science. Some of the largest corporations around the world have devoted massive research and development dollars to the field along with many Universities and Government Institutions due to the enormous potential of this technology.
- Functional quantum computers will impact almost every area of science and technology. Below is a list of some areas that will experience the most disruption:
  - Cyber Security/National Defense – Most of the encryption systems employed around the world that are used to safeguard everything from personal data like banking information to highly confidential corporate and governmental data, are based on prime factorization of large numbers. For classical computers the task of factoring the encryption keys is nearly impossible, but this is not the case for quantum computers as they would be able to break every encryption method currently used. New quantum encryption methods will need to be employed to ensure that data is protected.
  - Artificial Intelligence – Machine learning is based heavily on pattern recognition algorithms that crunch massive amounts of data. Quantum computers will allow for exponentially more processing power that will lead to fundamentally more powerful forms of A.I. at a rate faster than most currently believe possible with conventional computing systems.

Introduction to Practical Quantum Computing (cont.)

- Medicine/Chemistry – Quantum computing will allow scientists to to model complex molecular structures which is an extremely important aspect of new drug discoveries, and would even allow doctors to develop true patient-specific gene-therapy based treatments.
- Financial Industry – The finance industry could use the computational power of quantum computers to sort through enormous amounts of financial data, and use that information to optimize portfolios minute by minute.
- Climate Science – Quantum computers will give scientists the ability to model extremely complex weather patterns which will allow for more precise weather forecasts and could even lead to simulation-driven solutions to climate change.

- The reason Quantum Computers (QC) have the potential to disrupt so many different industries is because of the fundamental difference in how they operate compared to the supercomputers of today. Classical computing is built at a base level on bytes which are used to perform calculations and each bit represents either a 1 or 0. Quantum computing is built on quantum bits, known as qubits, and these particles not only represent 1's and 0's but due to the quantum mechanical property of superposition, can actually exist as both 1 and 0 at the same time and any combination in between. This means a small number of qubits grouped together would be able to do calculations exponentially faster than any of the supercomputers of today. In fact, it is estimated that a quantum computer that could successfully entangle as little as 50 qubits would be able to perform calculations faster than any classical computer, a level referred to as quantum supremacy, a mark companies like Google, IBM and Microsoft are actively trying to achieve. However there is not a consensus on the type of qubit that will be used to reach quantum supremacy.

Introduction to Practical Quantum Computing (cont.)

- There are five main types of qubits being used in the design of quantum computers: super-conducting qubits, silicon quantum dots, topological qubits, trapped ions and diamond vacancies.
  - Super-conducting qubits are based on existing circuit technologies used in current semiconductors however they are can lose their superposition state easily and must be kept at extremely low temperatures. Google and IBM are heavily invested in super-conducting qubits.
  - Silicon quantum dots are artificial atoms that made by adding an electron to a small piece of pure silicon. Like super-conducting qubits, they also must be kept in temperatures near absolute zero. Intel is working with quantum dots.
  - Topological qubits are quasiparticles that can be seen in the behavior of electrons channeled through semiconductor structures. Topological qubits would be practically immune to decoherence and thereby reduce the need for active error correction. However it is not yet a scientific certainty that topological qubits even exist. Microsoft is the only major company investing heavily in topological qubits.
  - Trapped ion quantum computers use lasers to cool and trap ions or electrically charged atoms which put them in a superposition state. Trapped ions are highly stable when compared to super-conducting qubits and quantum dots however it is also considerably slower from an operational perspective and requires an array of lasers.
  - Diamond vacancies are a qubit creation technique where a nitrogen atom and a vacancy add an electron to a diamond lattice and its quantum spin state is controlled via light. Diamond vacancies are the only qubit technology that can function at room temperature, however it is also the most difficult to entangle.

Note: Supporting Materials on QC obtained from: http://www.sciencemag.org/news/2016/12/scientists-are-close-building-quantum-computer-can-beat-conventional-one

Practical Quantum Computing Patent Landscape Report

- The present patent landscape report (PLR) covers worldwide published patent applications and grants in the space of quantum computers to make them practically feasible as well as their use.

- Due to the potential disruption this technology will cause it's not surprising to see so many different organizations represented in the patent landscape. For this reason, the PLR has been broken up into three different segments: a look at quantum computing from a corporate perspective, an academic perspective and a government perspective.

- Within each of the discussions, the patent families have been categorized into three groups based on the area covered in the invention: qubit technology, hardware and applications. There is further sub-categorization within each of those three main areas.

- Spatial concept maps labeled by the main concept areas, and further divided into sub-categories have been generated with colored highlights based on the key patent assignees by organization type.

GENERAL STATISTICS ON PRACTICAL QUANTUM COMPUTING

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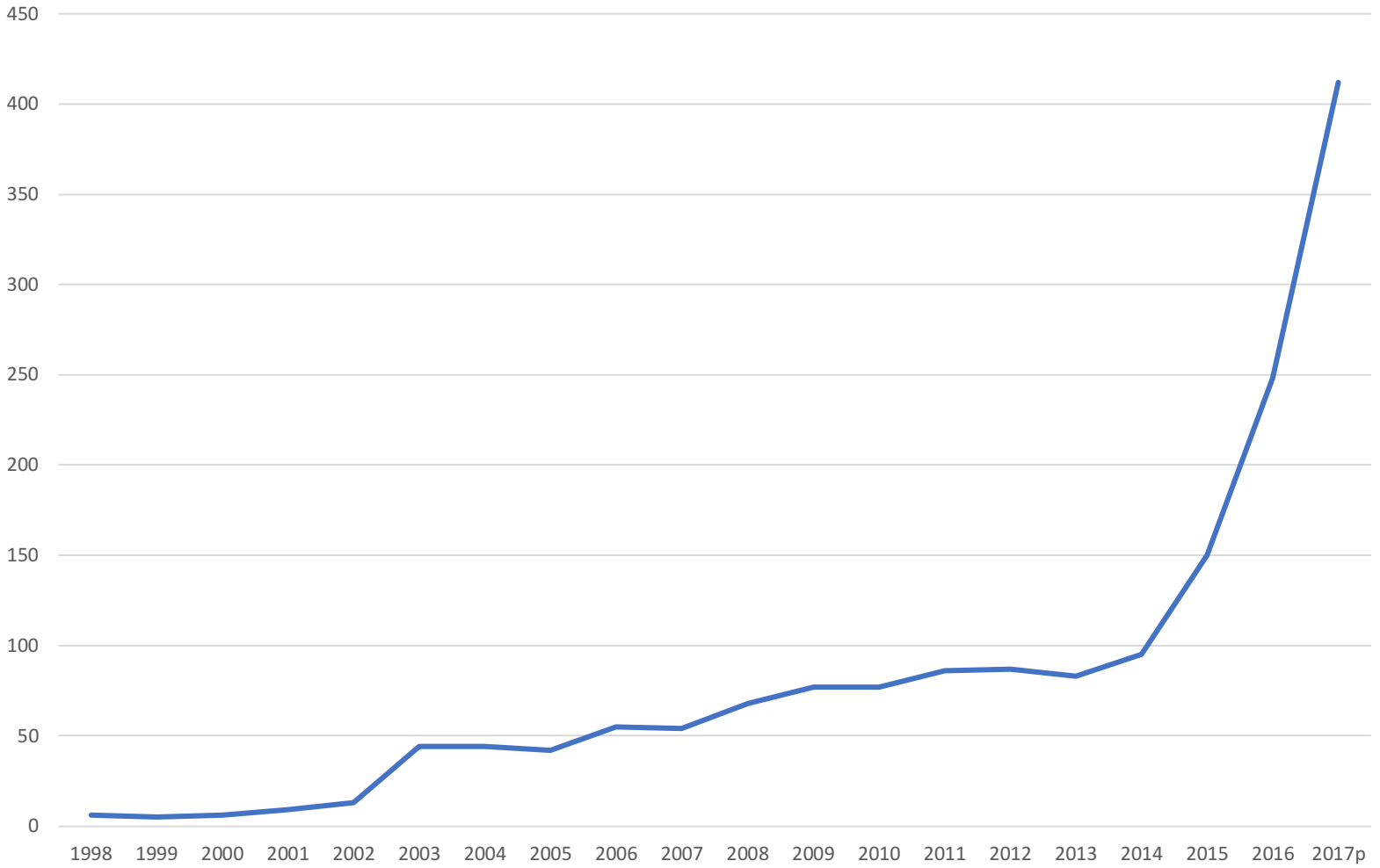
Overall Quantum Computing Patent Families by Publication Year

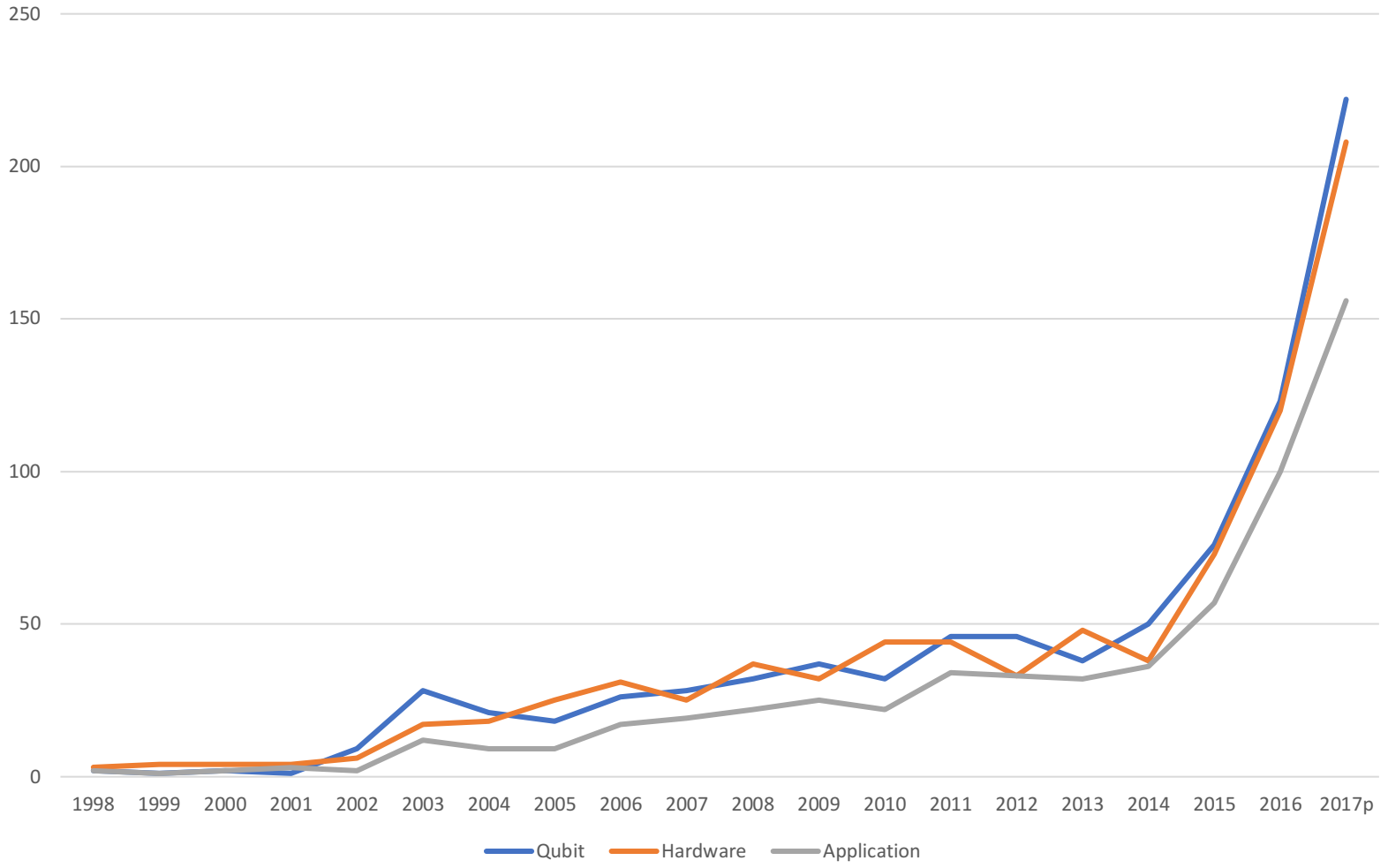
- The field of quantum computing has seen exponential growth over the last two years. This is projected to continue through 2017.
- In 2003 there was a jump in publications that continued with steady growth by an average of 17% per year through 2014.
- Since 2014 the count of patent families is projected to increase by 430% by the end of 2017.



Note: Based on 1,455 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 206 documents for 2017.

Quantum Computing Patent Families by Category and Publication Year

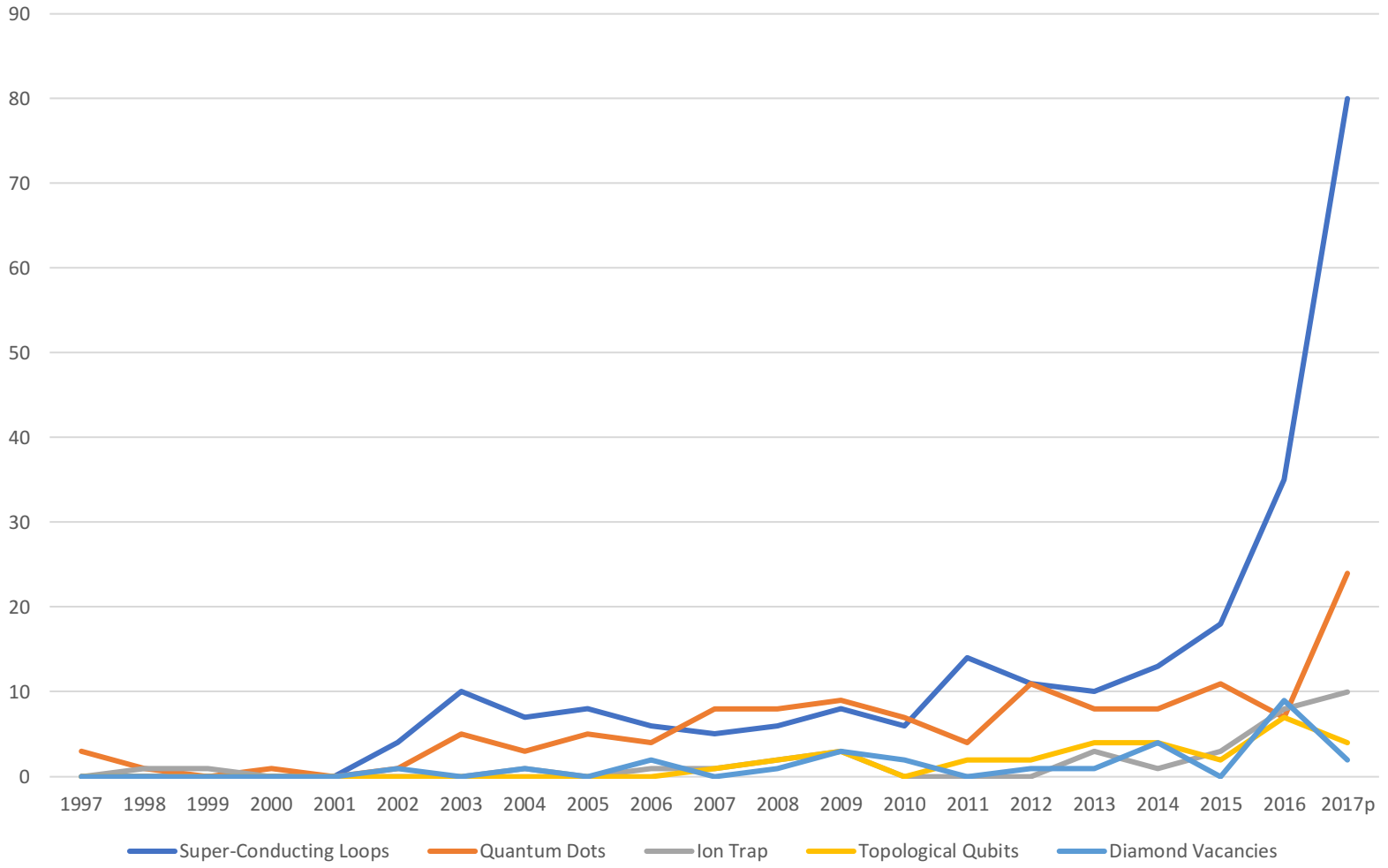
- The jump in the number of patent families in 2003 was driven primarily by documents related to qubit technologies, followed by hardware type and applications.
- Publications related to qubit technology and hardware have seen the greatest amount of growth over the period of rapid expansion that began in 2015 followed by applications.



Note: Based on 1,952 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category; Currently 293 documents for 2017.

Quantum Computing Patent Families by Qubit Type and Publication Year

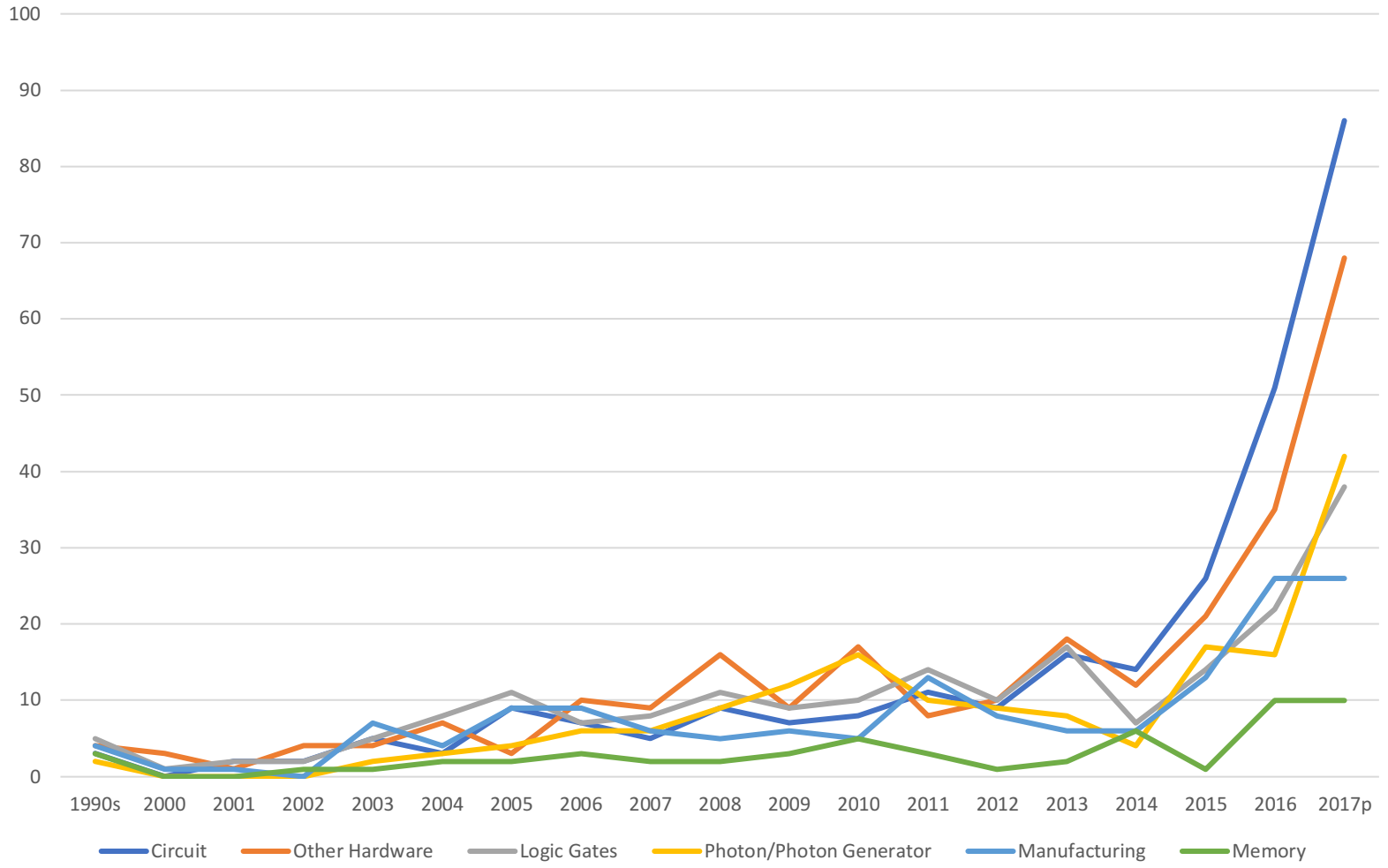
- Super-conducting qubits have been the main industry focus in terms of qubit technologies since 2002.
- For 2017 the number of publications related to super-conducting qubits is projected to be double the number of all other qubit types combined.
- Quantum dot qubit technology has historically been an area of strong interest and is projected to see a significant increase for 2017.
- Topological qubits and diamond vacancies technologies both project to decrease while families relating to ion trap qubits continues steady growth that began in 2015.



Note: Based on 402 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category; Currently 60 documents for 2017.

Quantum Computing Patent Families by Hardware Type and Publication Year

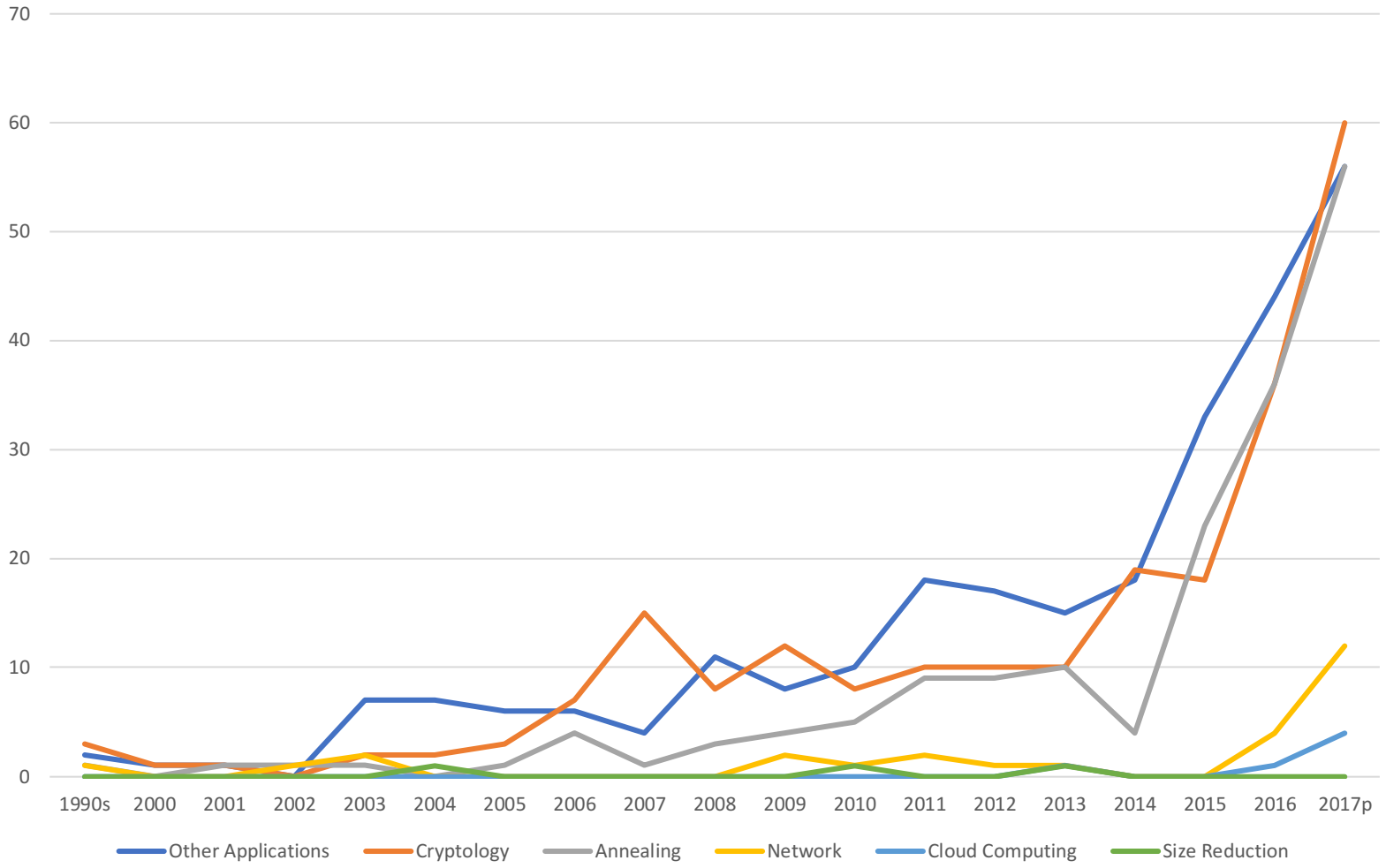
- Patent families related to quantum circuits and other hardware have seen the greatest increase over the last two years followed by publications addressing logic gates and photon generators.
- The other hardware category is composed primarily of records related to generic quantum information processing systems, generic quantum computing devices, and semiconductors.
- Manufacturing techniques had seen increases similar to those in logic gates and photon technologies since 2015 but look to be leveling off in 2017.



Note: Based on 976 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category; Currently 135 documents for 2017.

• Quantum Computing Patent Families by Application Type and Publication Year

- Cryptology and annealing are the most prevalent sub-categories in the Application category, and has grown rapidly since 2014.
- The other applications sub-category is made up mostly of publications related to quantum processing methods, and algorithms. These area are also experiencing rapid growth.
- Quantum computing patent families related to networks and cloud computing have both seen increases beginning in 2015 and are projected to continue through 2017.

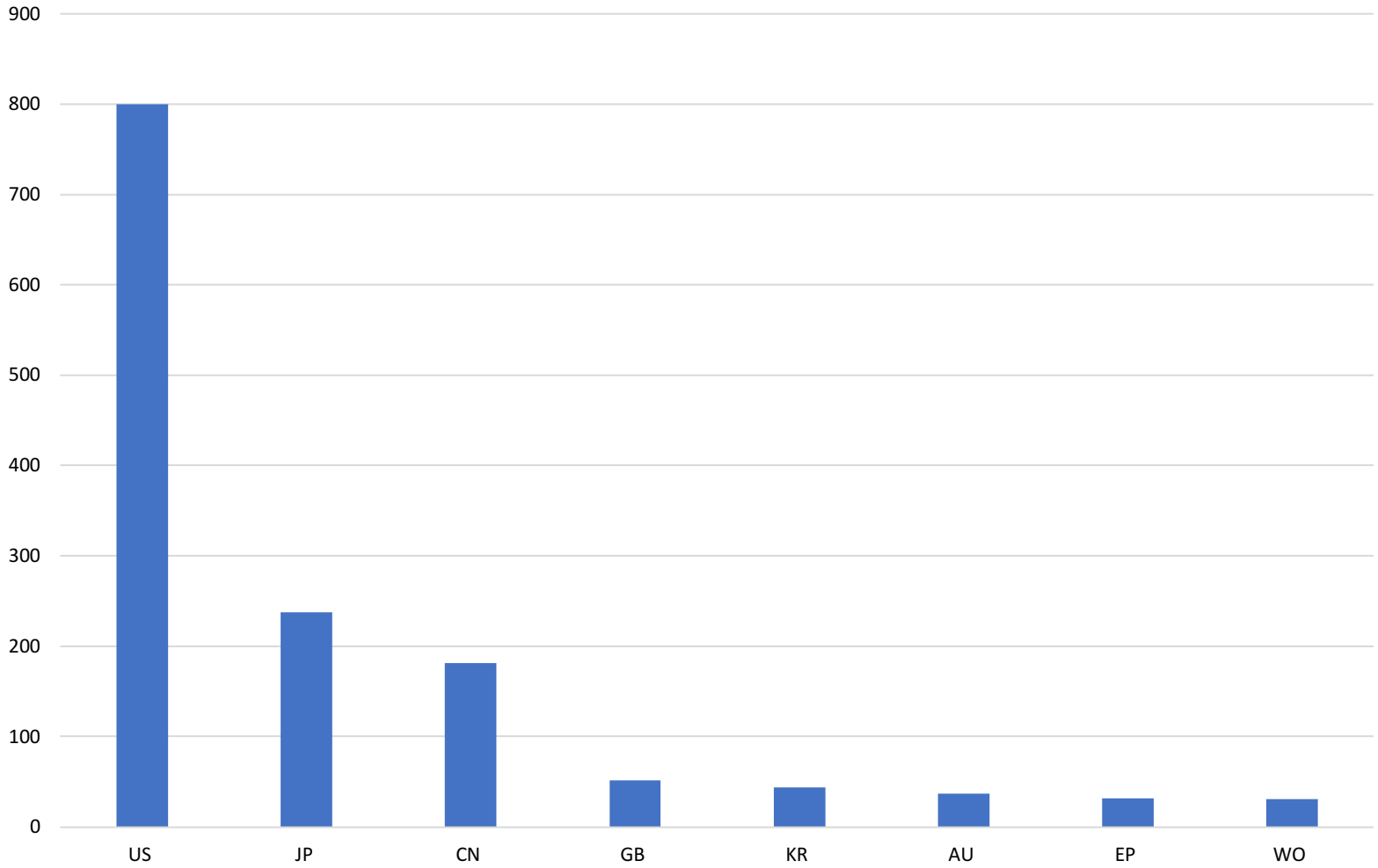


Note: Based on 600 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category; Currently 94 documents for 2017.

• Quantum Computing Patent Families by Priority Country

- In the quantum computing field the United States is far and away the most prominent country of priority filing. The U.S. has almost 3.5 times as many priority country publications as Japan (the second largest country).

- Japan and China are second and third respectively and are both more than 3.5 times larger than Great Britain (the fourth largest family producer).

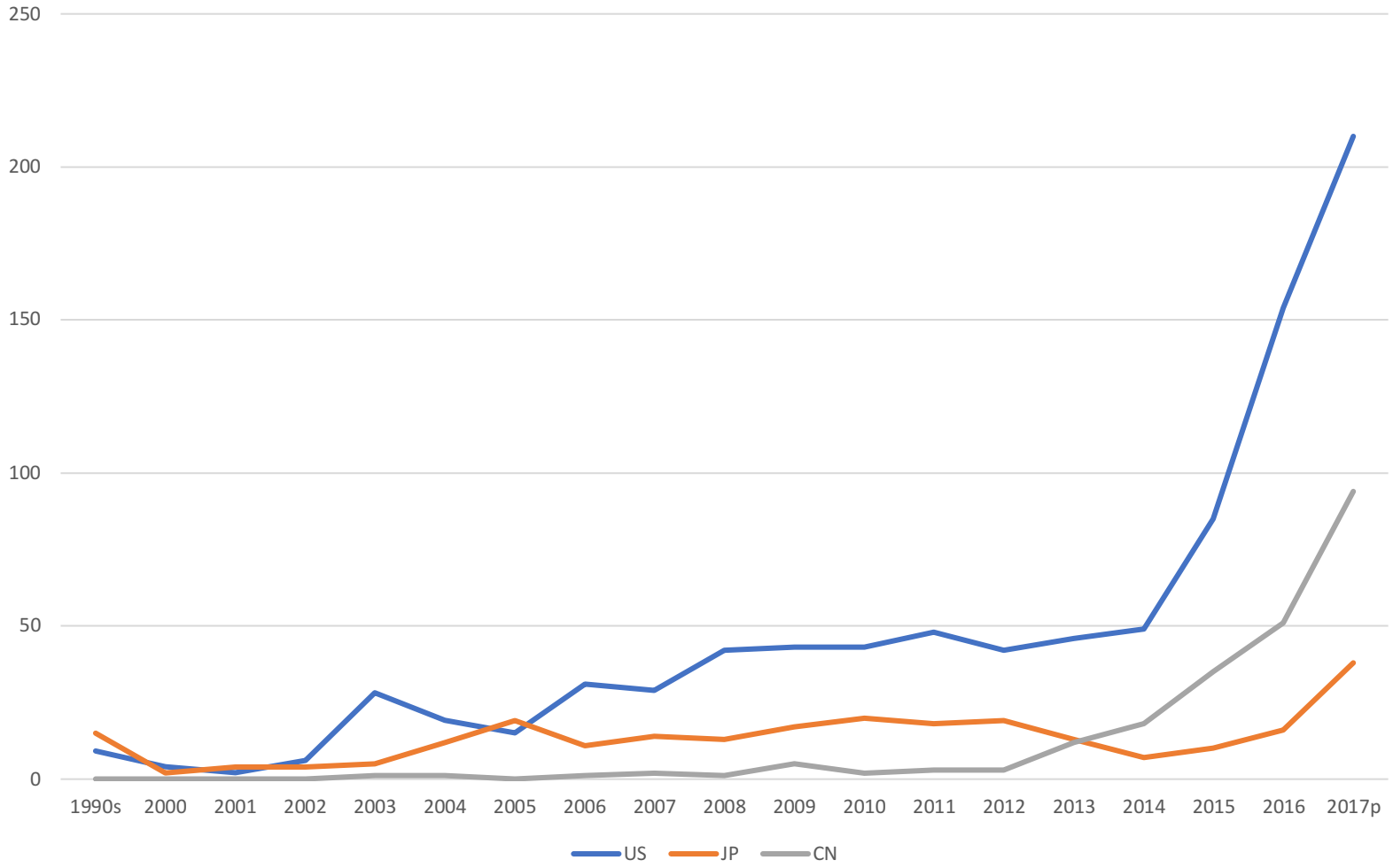


Note: Based on 1,416 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

• Quantum Computing Patent Families by Priority Country and Year

- The U.S. patent families follow a similar growth curve as the quantum computing industry as a whole, showing an increase in 2003 followed by exponential growth beginning in 2015.

- While Japan has a greater total number of publications where they are listed as the priority country, China overtook Japan in 2014 on a yearly basis, and is projected to grow at a rate of more than twice that of Japan for 2017.



Note: Based on 1,416 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

CORPORATE DISCUSSION ON PRACTICAL QUANTUM COMPUTING

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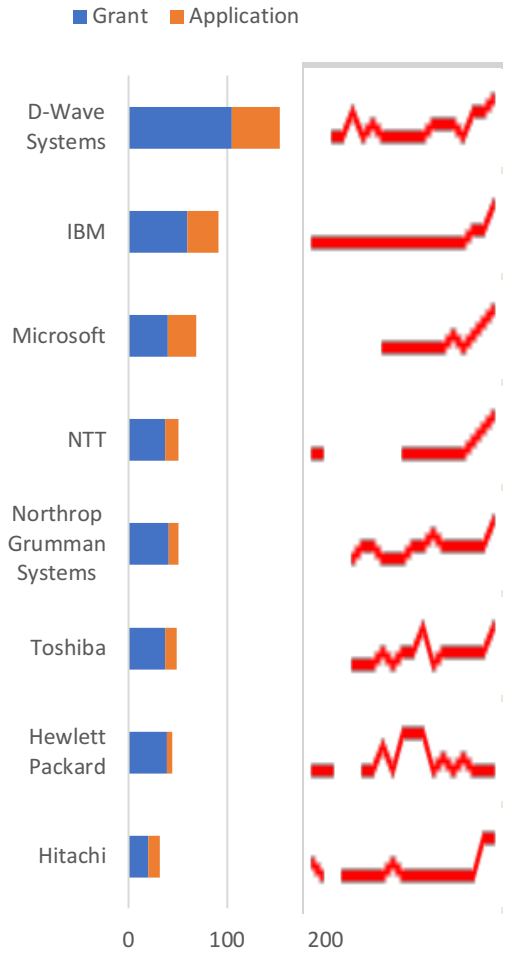
• Quantum Computing Patent Families by Top Companies

- All of the top assignees, except HP, and Hitachi are projected to see a massive surge in family publications in 2017.
- D-Wave Systems has the largest and one of the longest standing portfolio of quantum computing patent families in this study.
- While IBM's current portfolio is second in size to D-Wave, they project an explosion in families for 2017, doubling that of D-Wave for the year.
- Microsoft has been increasing the number of patents in their collection steadily since 2015.
- Northrop Grumman, Toshiba and NTT both project growth for 2017 .
- Hewlett Packard showed a strong interest in quantum computing patenting between 2005 and 2010 however they only have two publications since 2015.

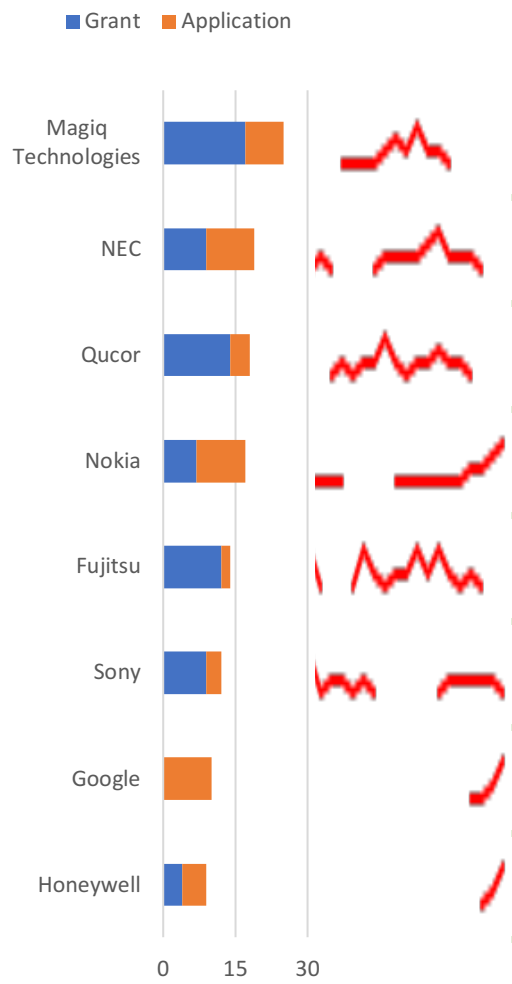


	1990s	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017p
D-Wave Systems				1	18	7	9	5	5	5	5	2	13	12	9	8	19	18	34
IBM	2		1	2	3			1		3	3	1	4	6	1	4	15	15	60
Microsoft									1	5	5	1	3	2	8	5	10	17	24
NTT	1										1	4	4	4	5	3	6	12	22
Northrop Grumman Systems						3	5	1	2	2	3	3	7	5	5	3	3	3	12
Toshiba						1	1	3	1	5	3	9	2	4	5	3	3	4	10
Hewlett Packard		1					2	5	1	7	7	9	2	4	1	3	1	1	
Hitachi	4				2	1	1		3	1	1	1	1		2	1	1	9	8

Note: Based on 540 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 85 documents for 2017.

Quantum Computing Patent Families by Top Companies (cont.)

- Google is new to quantum computing from a patenting perspective as illustrated by the fact that they do not currently have any granted patents. However they are adding to their portfolio rapidly.
- Honeywell is another newcomer to the field and are also growing fast.
- Magiq Technologies, NEC and Qucor all showed an interest in quantum computing from a patenting perspective in the early 2000s through around 2012 and have all trailed off since.
- Nokia has been steadily increasing their portfolio in quantum computing since 2014.

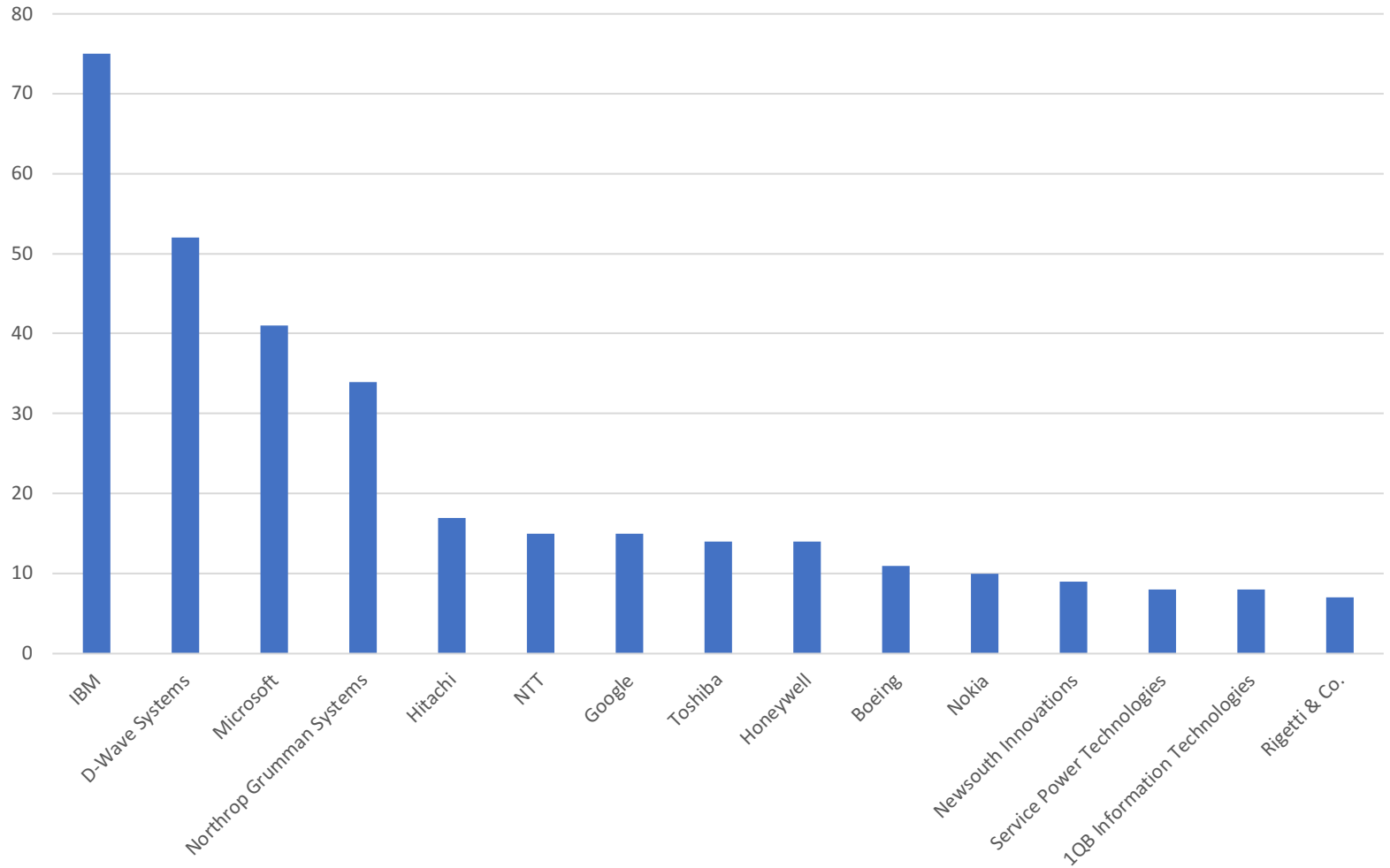


	1990s	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017p
Magiq Technologies					1	1		2	5	2	8	4	2						
NEC		1						1	2	2	2	3	4	2	1	1			
Qucor				2		2	1	4	1		1	2	3	1	1				
Nokia	1		1							1			1	1		2	3	4	6
Fujitsu	2					2	1		1	1	2	1	2	1		1			
Sony	4		1	1		1								1	1	1	1	1	
Google																	1	3	12
Honeywell																		4	10

Note: Based on 124 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 14 documents for 2017.

• Quantum Computing Patent Families by Top Companies since 2016

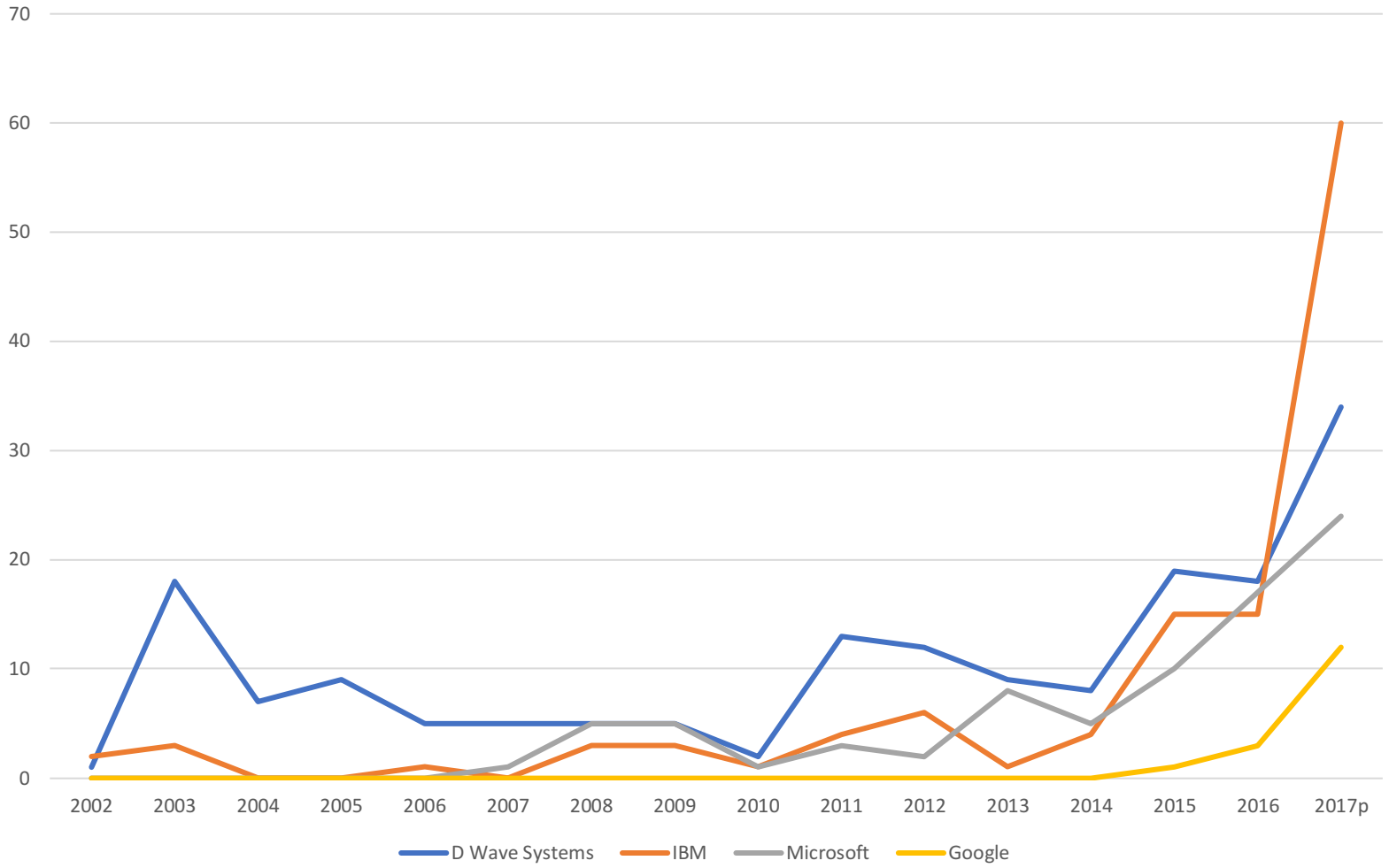
- Due to the rapid growth in the field of quantum computing over the last few years, looking at the top companies since 2016 gives a better view on the companies active now. IBM overtakes D-Wave Systems by a substantial margin in this metric, followed closely by Microsoft and Northrop Grumman.
- Google is closer to the top of the list in this view as well due to all of their work published in the last two years.
- Some smaller emerging companies also make the list now such as 1QB Technologies and Rigetti & Co.



Note: Based on 213 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 115 documents for 2017; Company totals include 2017 projections.

Quantum Computing Industry Leaders' Patent Families by Year

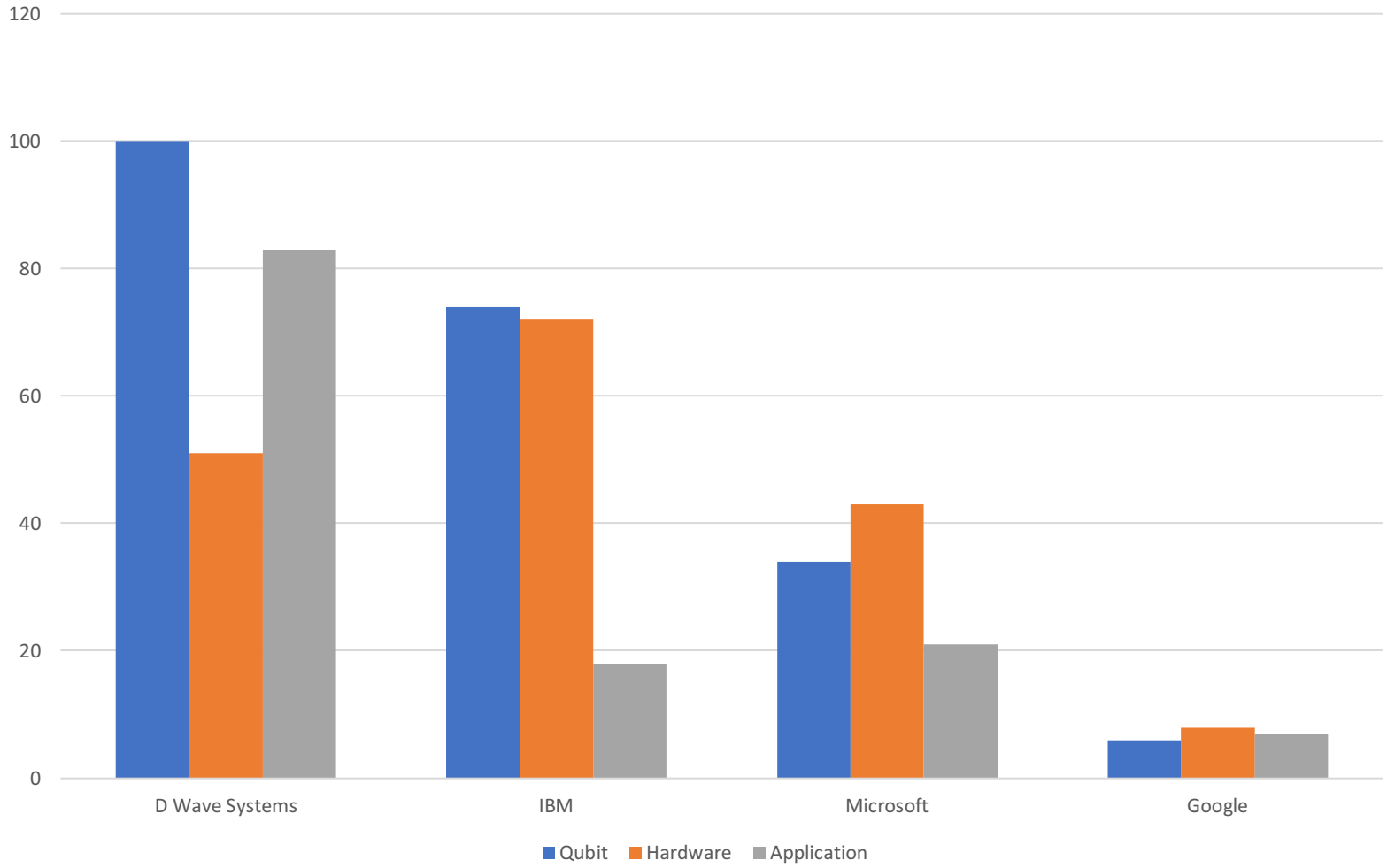
- Looking at the industry leading companies patent families by year clearly shows D-Wave's historical industry dominance from a patenting perspective.
- However, it's also clear that 2017 is set to be huge year for IBM in this field with the projected number of families growing in a near vertical line.
- Microsoft has been active since 2007 and also shows solid growth since 2015 that has a similar slope to the projected number of families from D-Wave.
- Google was a late entrant into quantum computing but are rapidly growing with four documents publishing in June alone.



Note: Based on 320 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 65 documents for 2017.

Quantum Computing Industry Leader's Portfolio Breakdowns by Invention Category

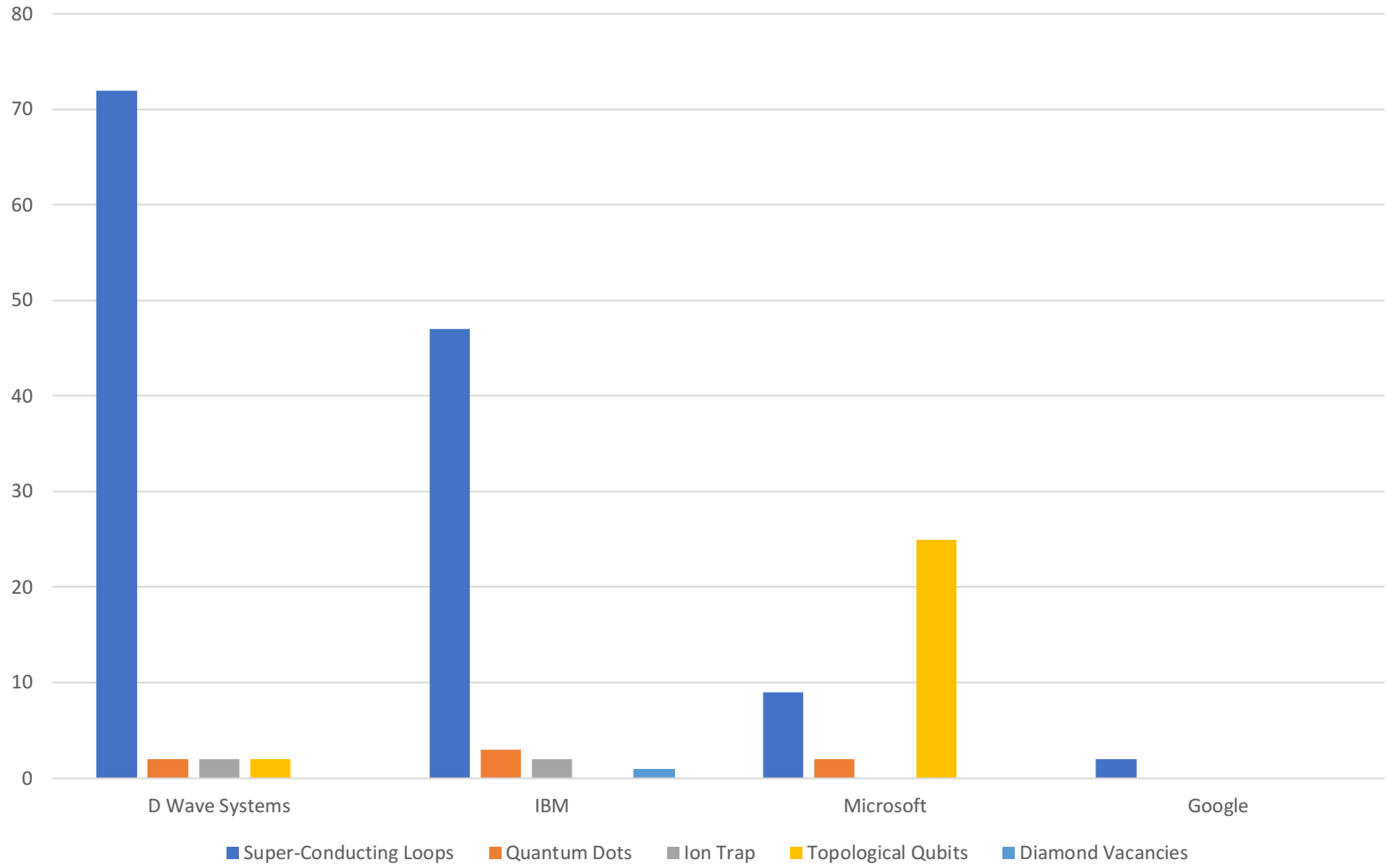
- Looking at D-Wave Systems portfolio they tend to focus on qubit technology and applications more than hardware, though they still have a fair number of hardware patent families.
- IBM and Microsoft on the other hand show more interest in qubit technology and hardware, and less focus on applications.
- Google has a younger, smaller portfolio overall, but currently they seem to be investing in all three categories.



Note: Based on 517 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Industry Leader's Portfolio Breakdowns by Qubit Type

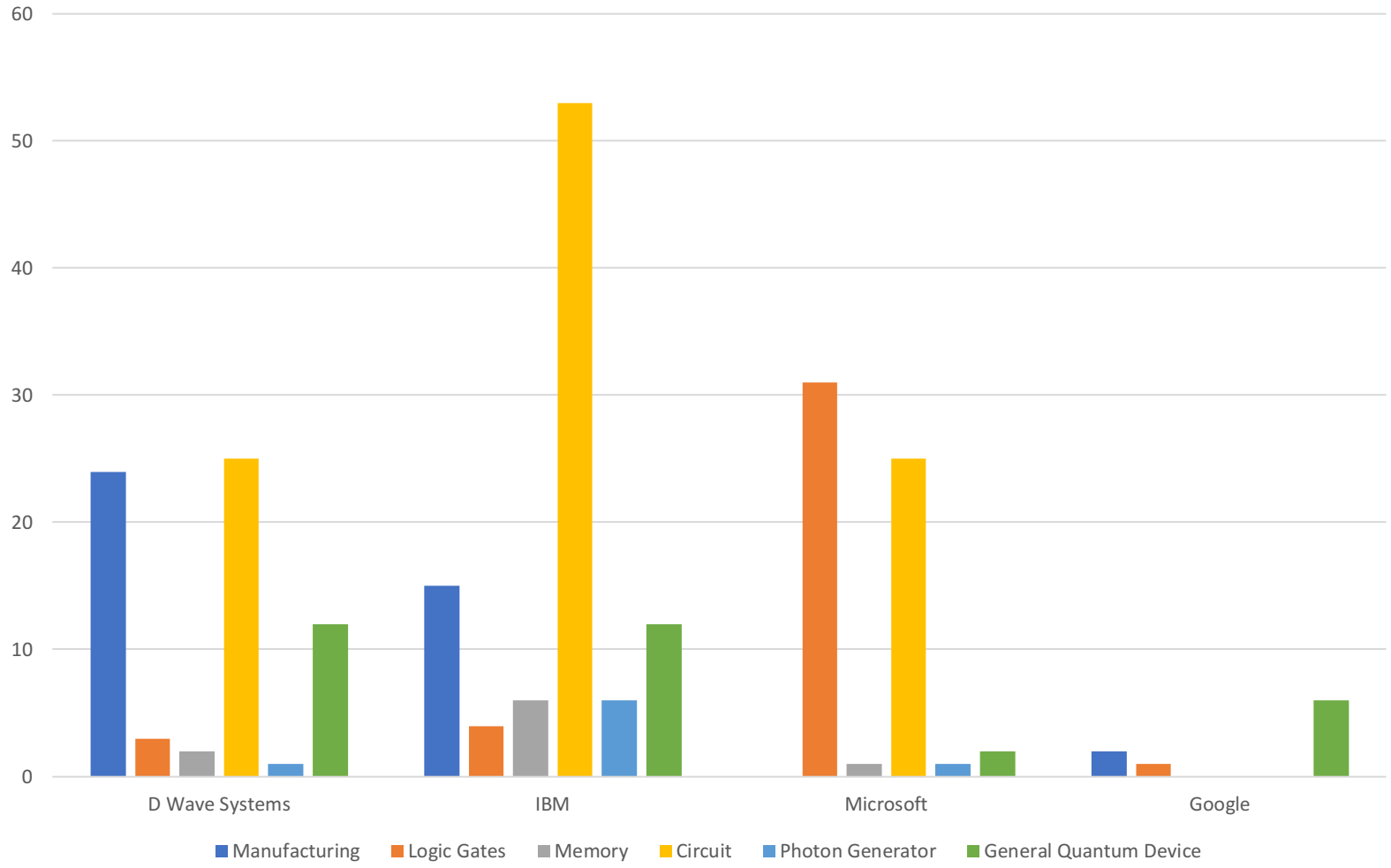
- D-Wave Systems and IBM are both invested in super-conducting qubit technologies.
- While Microsoft has shown interest in super-conducting technologies, they are clearly focused on topological qubit technologies. In fact, there are only 28 patent families in this study related to topological qubits and 25 are owned by Microsoft.
- Google has two publications dealing with qubit types and both are in super-conducting technologies.



Note: Based on 169 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

Quantum Computing Industry Leader's Portfolio Breakdowns by Hardware Type

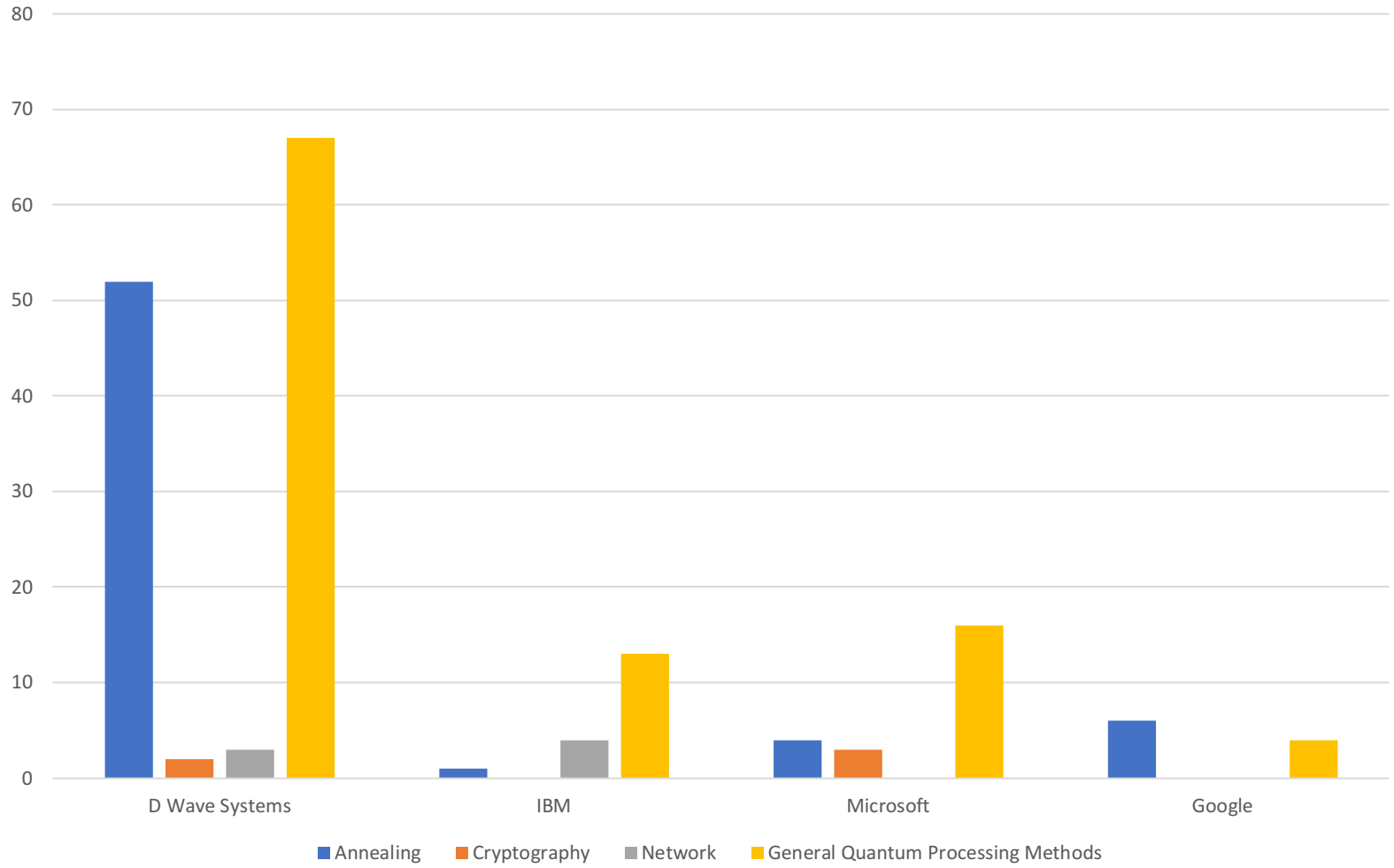
- D-Wave Systems focus in hardware mainly centers around circuits and manufacturing techniques.
- IBM also has strong interest in building quantum circuits however they are invested in all other areas within the hardware category.
- Microsoft has four times as many publications related to logic gates than the other three companies combined. They are also interested in circuits.
- Google's limited portfolio is made up primarily of generic quantum chips.



Note: Based on 232 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

Quantum Computing Industry Leader's Portfolio Breakdowns by Application Type

- Over 33% of D-Wave Systems entire portfolio is related to quantum annealing.
- Six of the ten patent families that make up Google's entire collection are related to quantum annealing.
- IBM and Microsoft's Other Applications are comprised of publications related to quantum algorithms and simulations.



Note: Based on 175 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

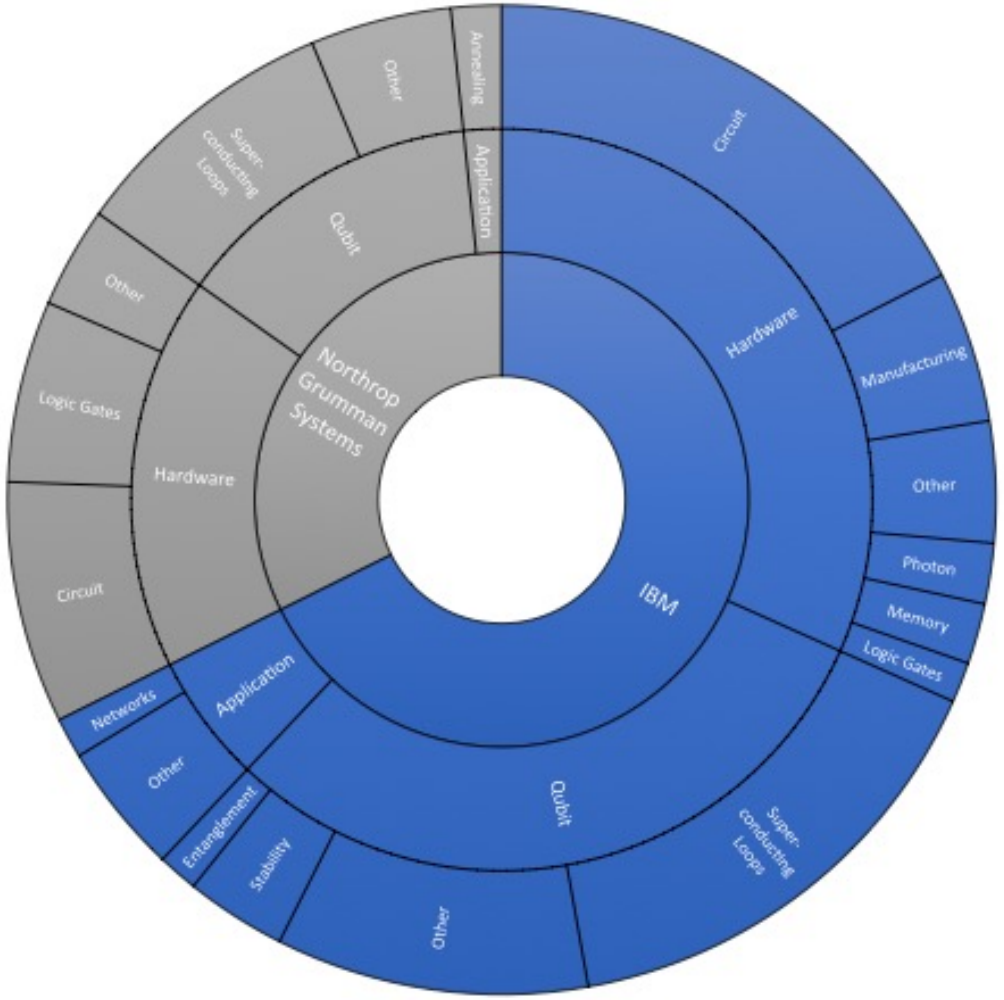
Intel's Quantum Computing Portfolio Breakdown by Patent families they Cited from the QC Collection

- Intel is another major corporation that is heavily invested in quantum computing, but they are not very active from a patenting perspective as they have just five patent families.
- However, Intel does cite a large number of the patents in the quantum computing collection for other inventions not directly related to this field.
- Of the documents that Intel cites that are captured in this collection, they show slightly more interest in hardware than qubit technology and applications.
- Within the Qubit Technology the publications are mainly focused on silicon quantum dots followed by super-conducting qubits. The Hardware Category is made up of documents related to manufacturing techniques, circuits and logic gates.
- Cryptography is the focus in the Applications.

Note: Based on 18 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

IBM vs Northrop Grumman Systems Portfolio Breakdown by Sunburst Chart

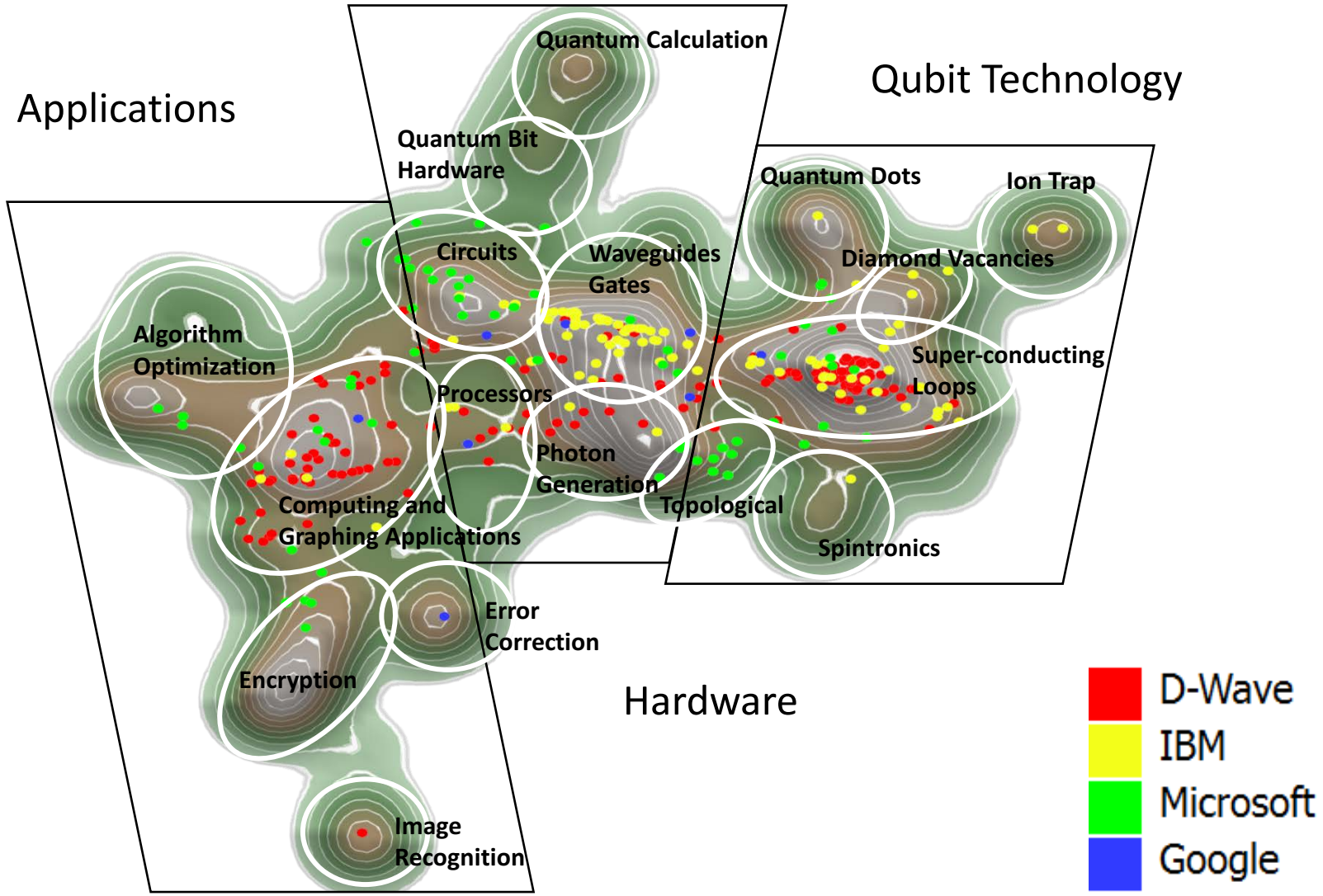
- A company interested in competing with IBM should have a closer look at Northrup Grumman portfolio.
- When compared side-by-side both Northrop and IBM have made significant investments in super-conducting qubit technologies.
- Both organizations are also interested in circuits on the hardware side, but Northrup has a larger percentage focused on logic gates.



Note: Based on 303 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Patent Families Spatial Concept Map by Top Companies

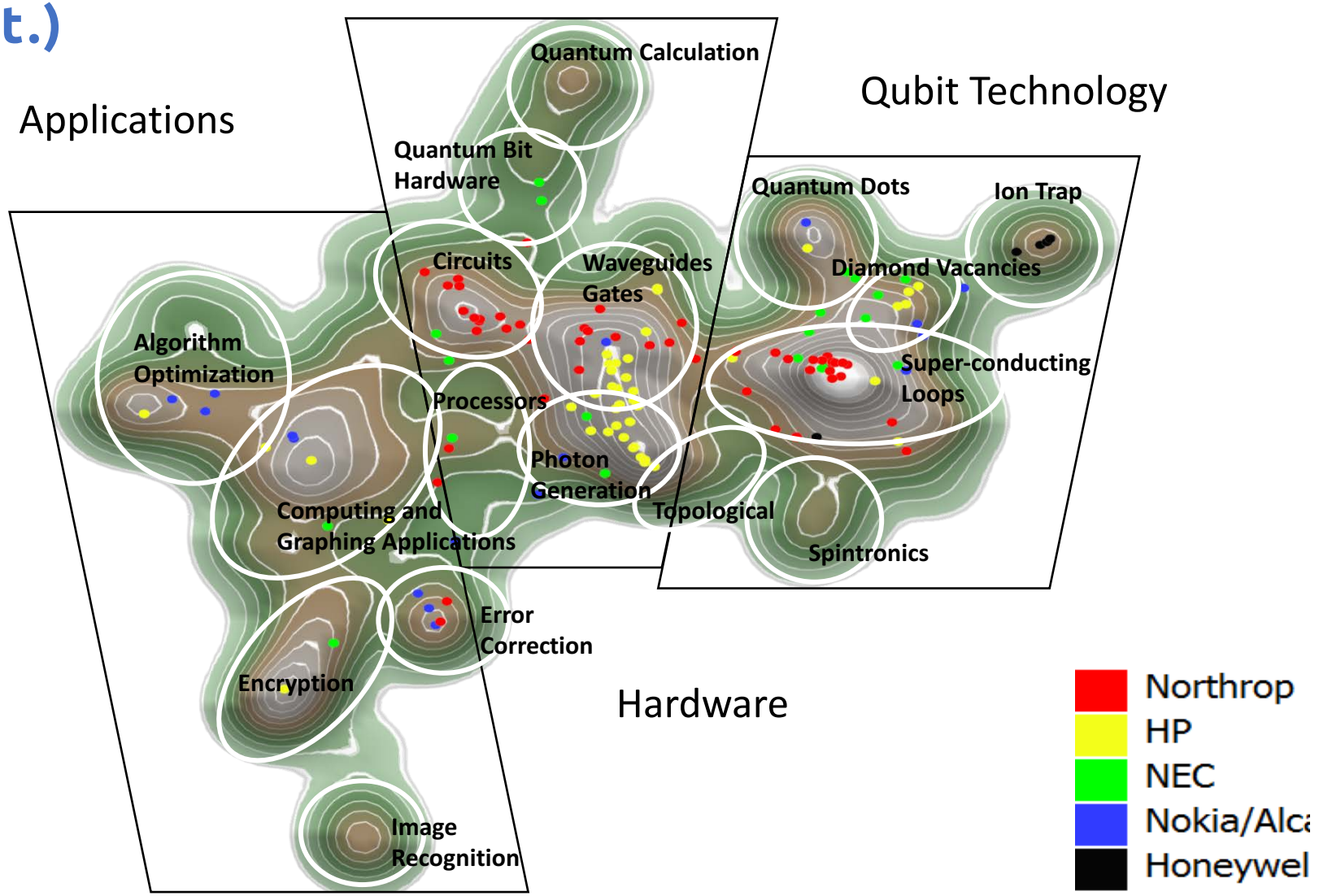
- D-Wave has a high concentration of their portfolio in super-conducting technologies, it's clear from this map that their other focus area is in the computing and graphing applications area where they are the dominant player of the four major companies.
- IBM also has a nice concentration in super-conducting technologies and they are the only one of the big four that has shown interest in diamond vacancies and ion trap qubit technologies. IBM is leading the way in waveguides and logic gates shown by their dense clustering in that space.
- Microsoft is the only company working with topological qubit technologies and they are also heavy into circuit hardware. Microsoft also shows the most range in terms of application interests with dispersion throughout that area.
- Google is clearly lagging behind from a patenting perspective compared to the others.



Note: Based on 323 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

Quantum Computing Patent Families Spatial Concept Map by Top Companies (cont.)

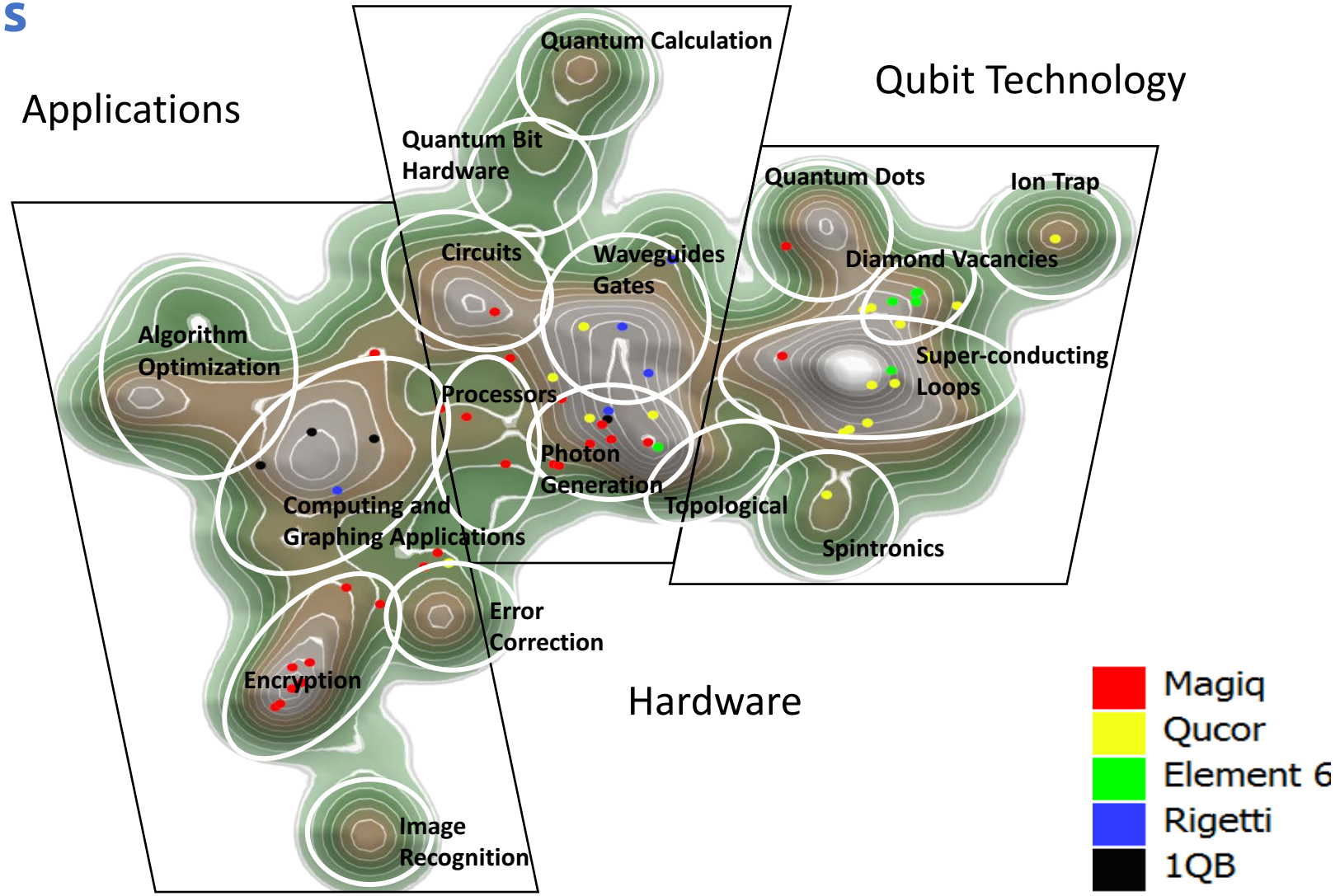
- Northrop Grumman has a very similar distribution to IBM from the previous slide with clustering shown in super-conducting, waveguides, logic gates and circuits.
- HP has a dense clustering in the hardware category in the photon and logic gate fields. They also show another small array in diamond vacancies.
- NEC has the greatest concentration in the qubit technology category spread between diamond vacancies, super-conducting loops and quantum dots but they also have a decent representation throughout the hardware category.
- Nokia/Alcatel, while having a smaller overall portfolio than the previous companies, appears to be evenly distributed across the map unlike Honeywell which is almost entirely centered in ion traps.



Note: Based on 140 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

Quantum Computing Patent Families Spatial Concept Map by Emerging Companies

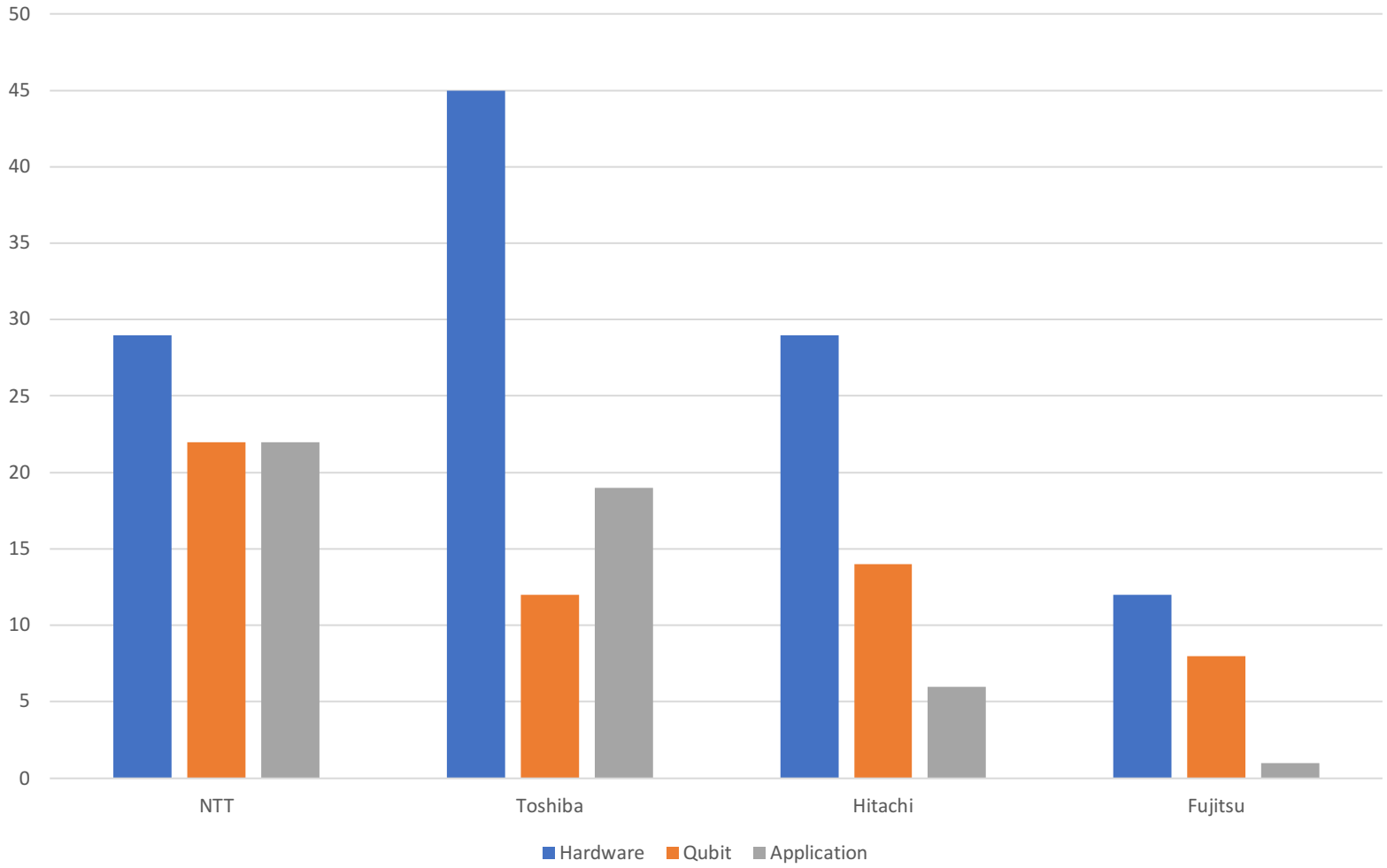
- Magiq Technologies collection is clustered in encryption, photon generation and quantum processors which is the opposite of Qucor who also has some interest in photons but is mainly spread across qubit technologies within super-conducting and diamond vacancies.
- Element Six, the synthetic diamond manufacturer, has the bulk of their collection located in the diamond vacancies area of the map.
- Most of Rigetti's portfolio is located in waveguides and logic gates with one document in computing applications however they have nothing in the qubit technology area.
- 1QB Information Technologies have a small collection that is mainly focused around computing and graphing applications.



Note: Based on 59 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

Quantum Computing Top Japanese Portfolio Breakdowns by Invention Category

- Inventions related to hardware appear to be the focus for the top Japanese firms in the quantum field especially Toshiba and Hitachi which is the opposite of the top U.S. companies who have more interest in qubit technologies followed by hardware.
- NTT has an interest in all three of the categories, however their portfolio is related more towards quantum communication than universal quantum computing.
- Fujitsu and Hitachi show a greater focus on qubit technologies than applications which is opposite Toshiba.

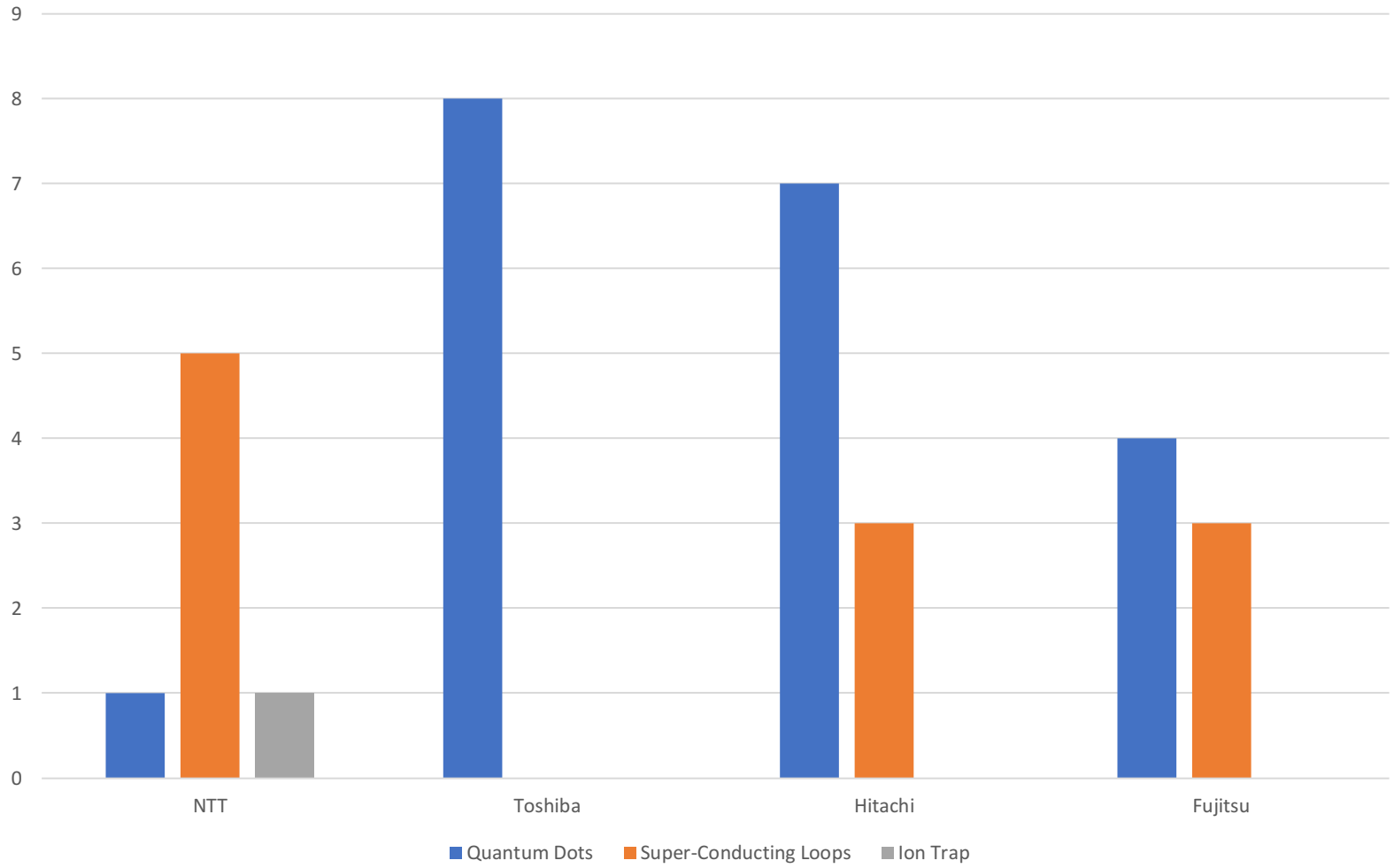


Note: Based on 219 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Top Japanese Portfolio Breakdowns by Qubit Type

- Quantum dot technology is the primary qubit type of interest followed closely by super-conducting qubits for the top Japanese companies except for NTT, who has the largest collection related to super-conducting qubit technologies.

- NTT is also the only firm to have any patent families that deal with qubit types (ion trap) other than quantum dots and super-conducting qubits.

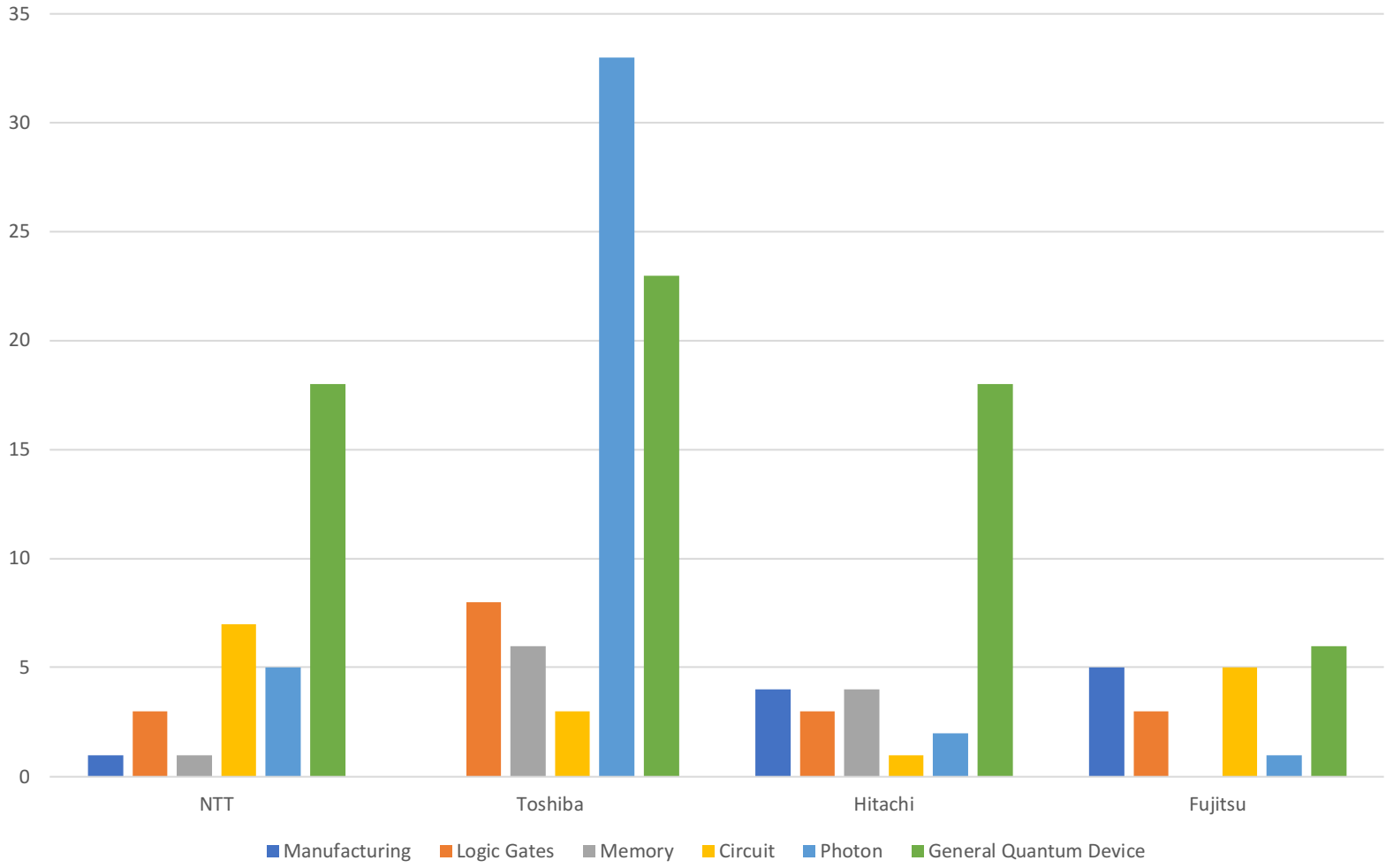


Note: Based on 32 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Top Japanese Portfolio Breakdowns by Hardware Type

- Much of the portfolios for all the top Japanese companies are made up of publications related to general quantum hardware and devices which differs from the top U.S. firms who are more focused on individual components like circuits, logic gates and manufacturing techniques from a hardware perspective.

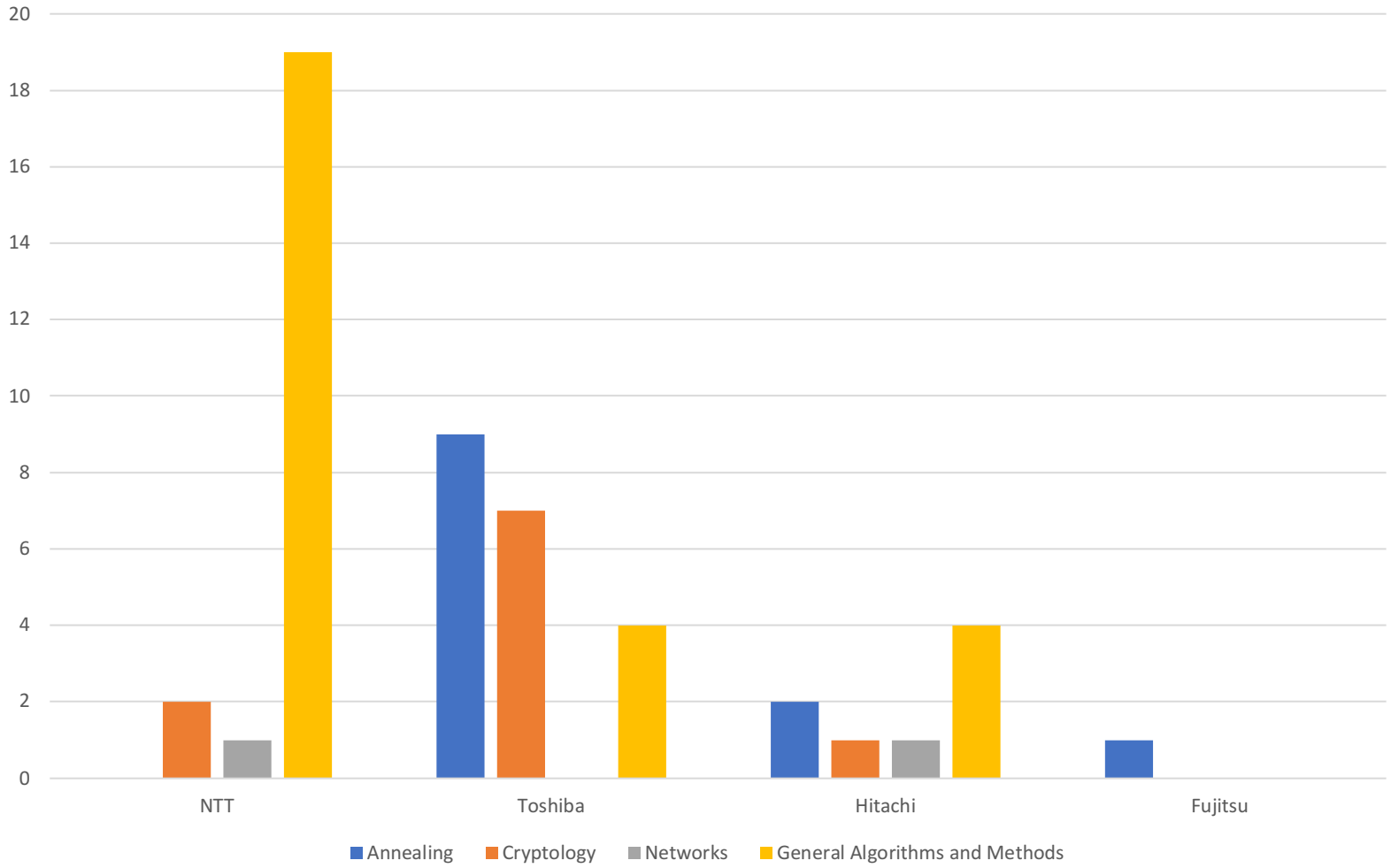
- Over 67% of Toshiba's portfolio is related to photons and photon generators.



Note: Based on 160 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Top Japanese Portfolio Breakdowns by Application

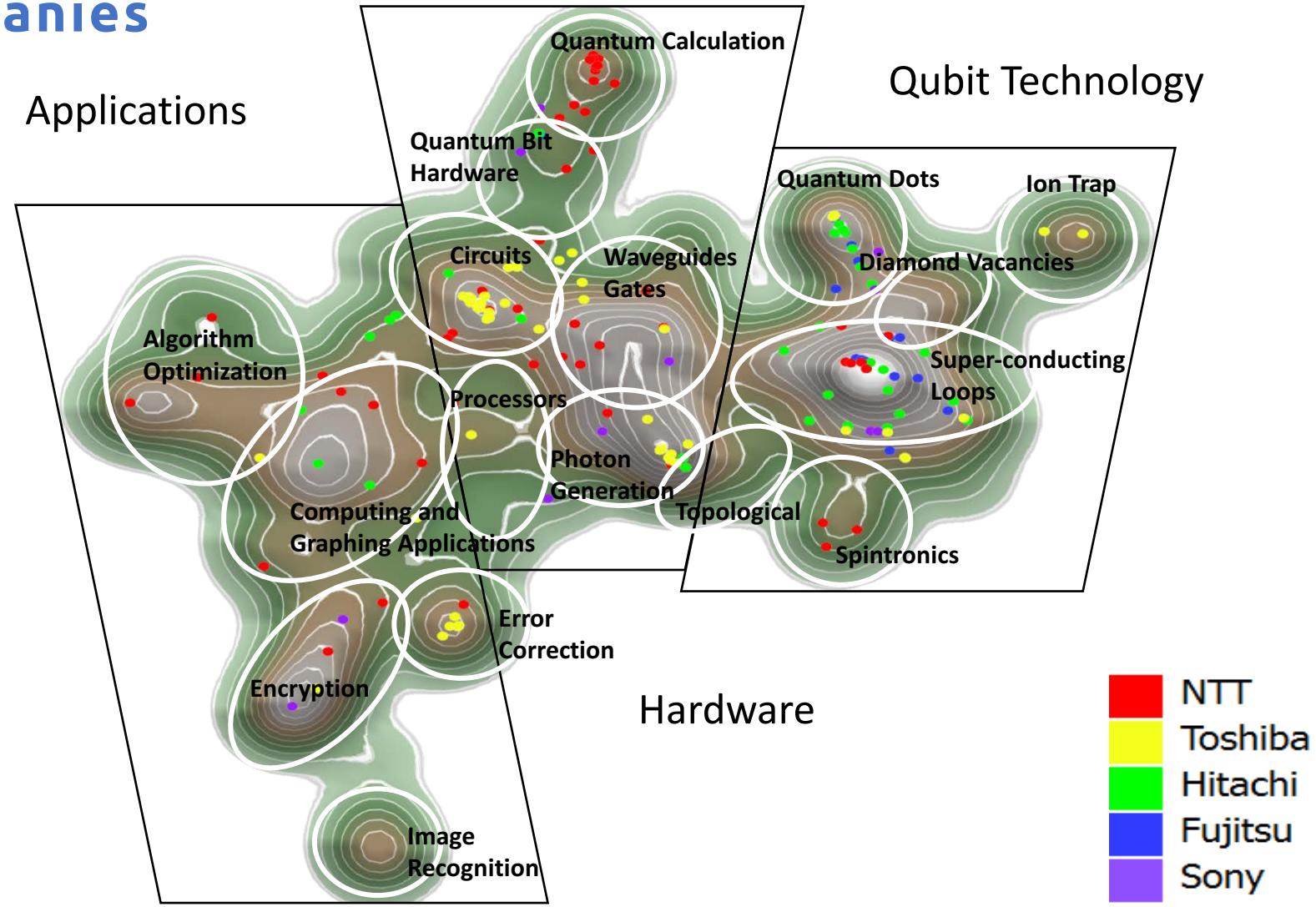
- Almost 40% of NTT's entire portfolio is related to general algorithms and processing techniques unlike Toshiba which is more focused on specific annealing and other optimization algorithms and cryptology.
- Hitachi has at least some interest in all four of the application categories while Fujitsu has just one patent family in the application category in total.



Note: Based on 51 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Patent Families Spatial Concept Map by Top Japanese Companies

- While NTT has a tight cluster in quantum calculation, the rest of their portfolio is evenly distributed across the map.
- Toshiba has three main pockets of interest: circuits, photons and error correction. They also have work spread throughout the qubit technology category mainly in quantum dots with some overlap with super-conducting loops.
- The bulk of Hitachi's portfolio is made up of work in qubit technology in super-conducting loops and quantum dots but they are also spread across the hardware and application categories around circuits and computing applications.
- Fujitsu is focused entirely on qubit technology, mainly in super-conducting qubits but also quantum dots.
- Most Sony documents are spread throughout qubit technology and hardware.



Note: Based on 158 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

ACADEMIC DISCUSSION ON PRACTICAL QUANTUM COMPUTING

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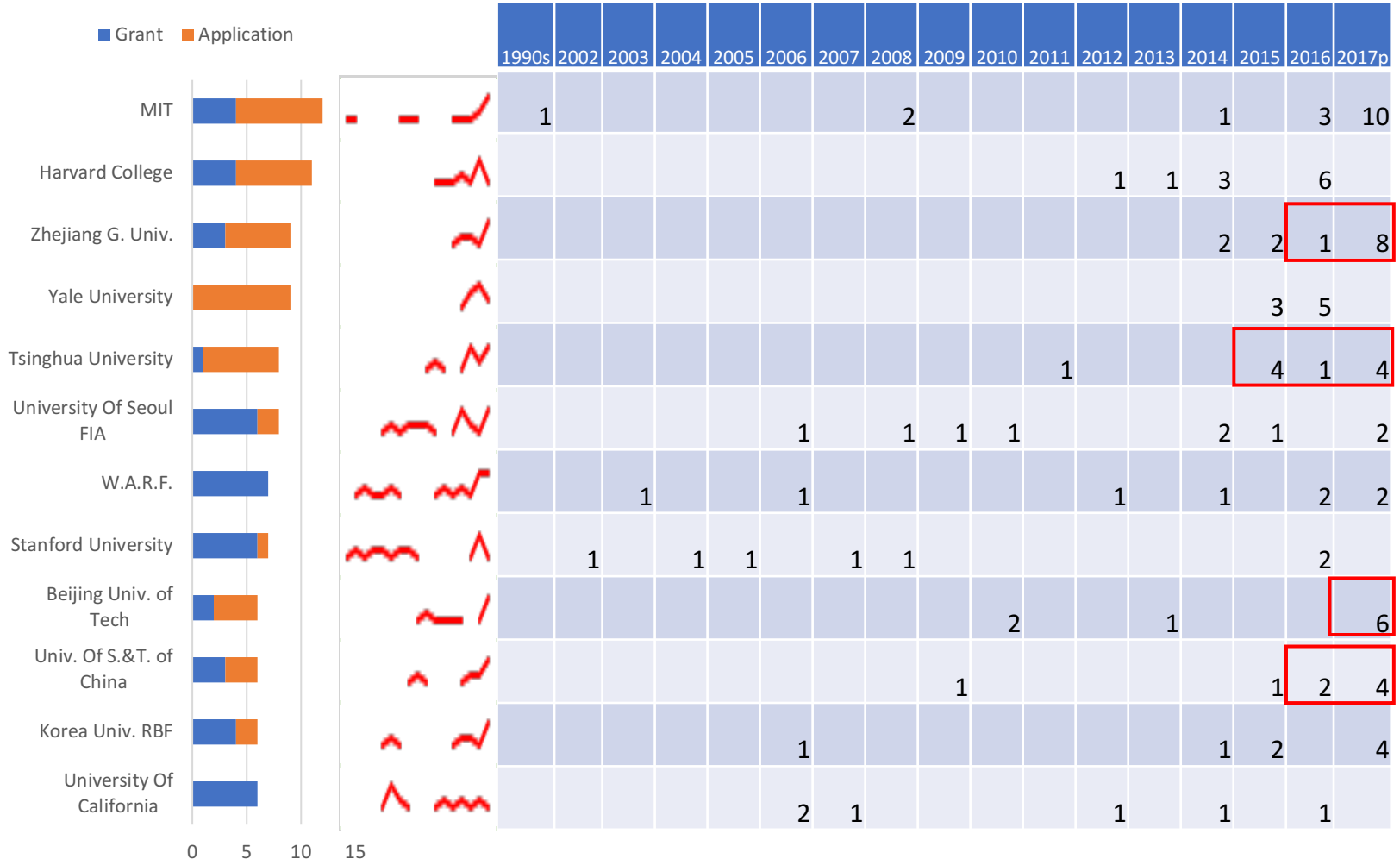
• Quantum Computing Patent Families by Top Universities

- Patenting in quantum computing from an academic perspective is a relatively recent occurrence compared to the corporate world as evidenced by the 3:1 ratio of applications to grants for the five largest universities combined. Stanford, WARF, and Univ. of Seoul are noticeable excepts with sustained interested and more grants than apps.
- While American Universities MIT, Harvard and Yale make up three of the top four largest collections overall, there are more publications projected to come from Chinese Universities in 2017 then all other countries on this list combined (highlighted in red).

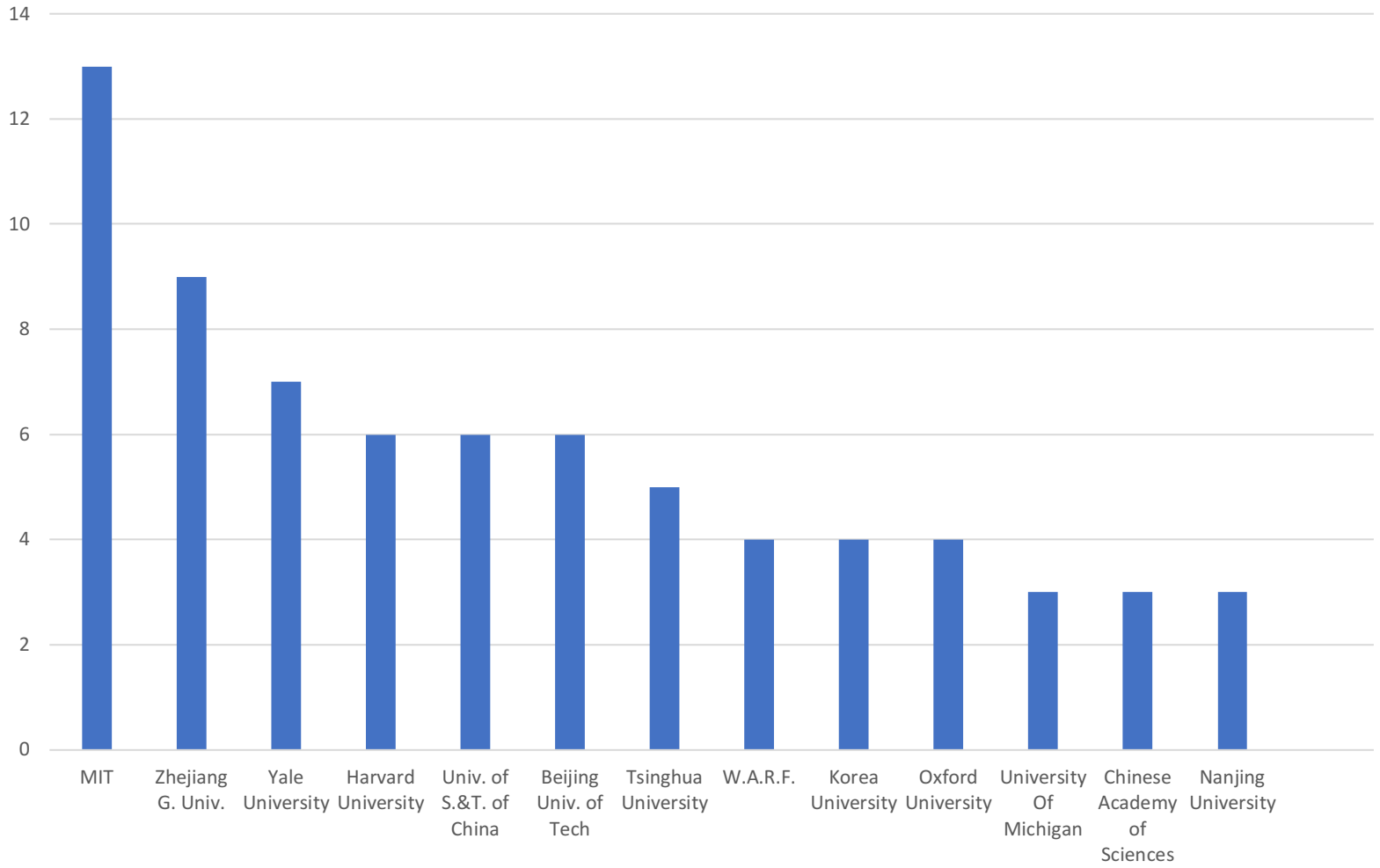


	1990s	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017p
MIT	1							2						1		3	10
Harvard College												1	1	3		6	
Zhejiang G. Univ.														2	2	1	8
Yale University															3	5	
Tsinghua University											1				4	1	4
University Of Seoul FIA						1		1	1	1				2	1		2
W.A.R.F.			1			1						1		1		2	2
Stanford University		1		1	1		1	1								2	
Beijing Univ. of Tech										2			1				6
Univ. Of S.&T. of China									1						1	2	4
Korea Univ. RBF						1								1	2		4
University Of California						2	1					1		1		1	

Note: Based on 95 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 21 documents for 2017.

• Quantum Computing Patent Families by Top Universities since 2016

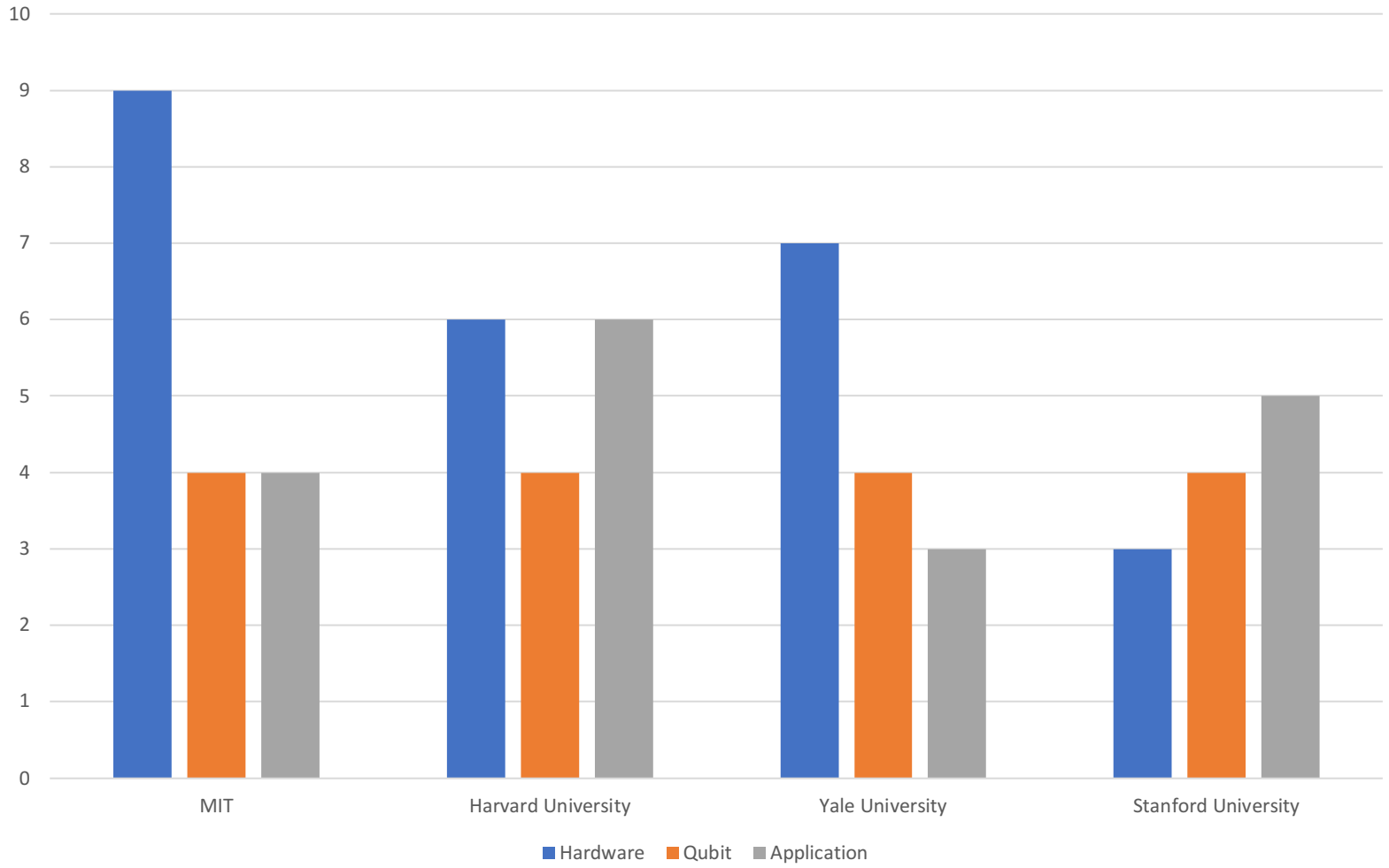
- MIT is currently very active in quantum computing from a patenting perspective, having five applications published through the first six months of 2017, followed closely by Zhejiang University who have four.
- Overall though Chinese Universities make up six of the top 13 positions when looking at the largest number of publications over the last two years, and more than half of the total number of patent families.



Note: Based on 61 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 27 documents for 2017; University totals include 2017 projections.

Quantum Computing Academic Leader's Portfolio Breakdowns by Invention Category

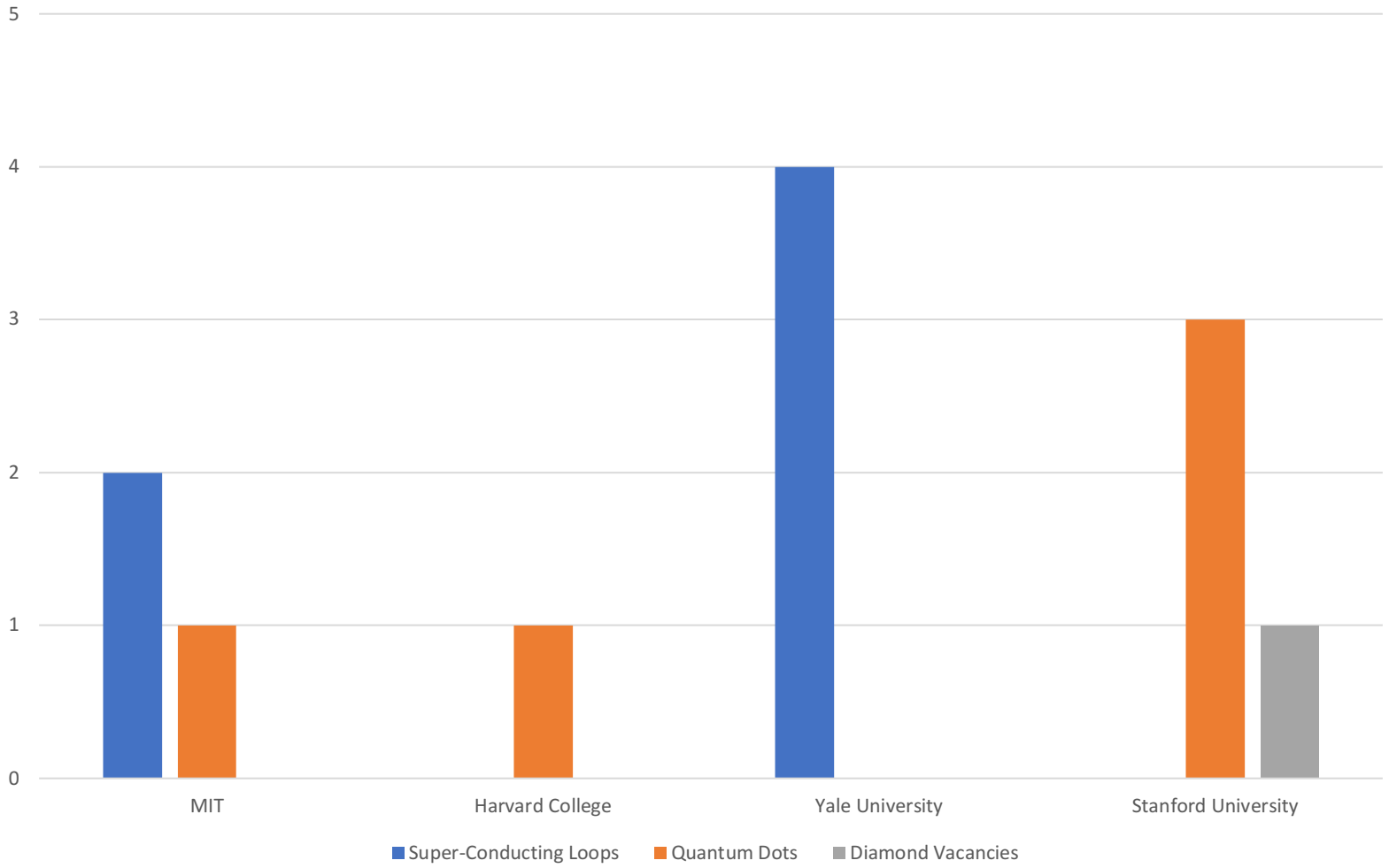
- Over half of MIT's collection of patent families are related to hardware while the rest is split equally between qubit technology and applications.
- Harvard has a relatively equal distribution across the three categories with slightly more interest in hardware and applications.
- The majority of Yale's portfolio is related to hardware followed qubit technologies and applications while Stanford's exactly opposite with the most documents related to applications followed by qubits and hardware.



Note: Based on 59 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Academic Leader's Portfolio Breakdowns by Qubit Type

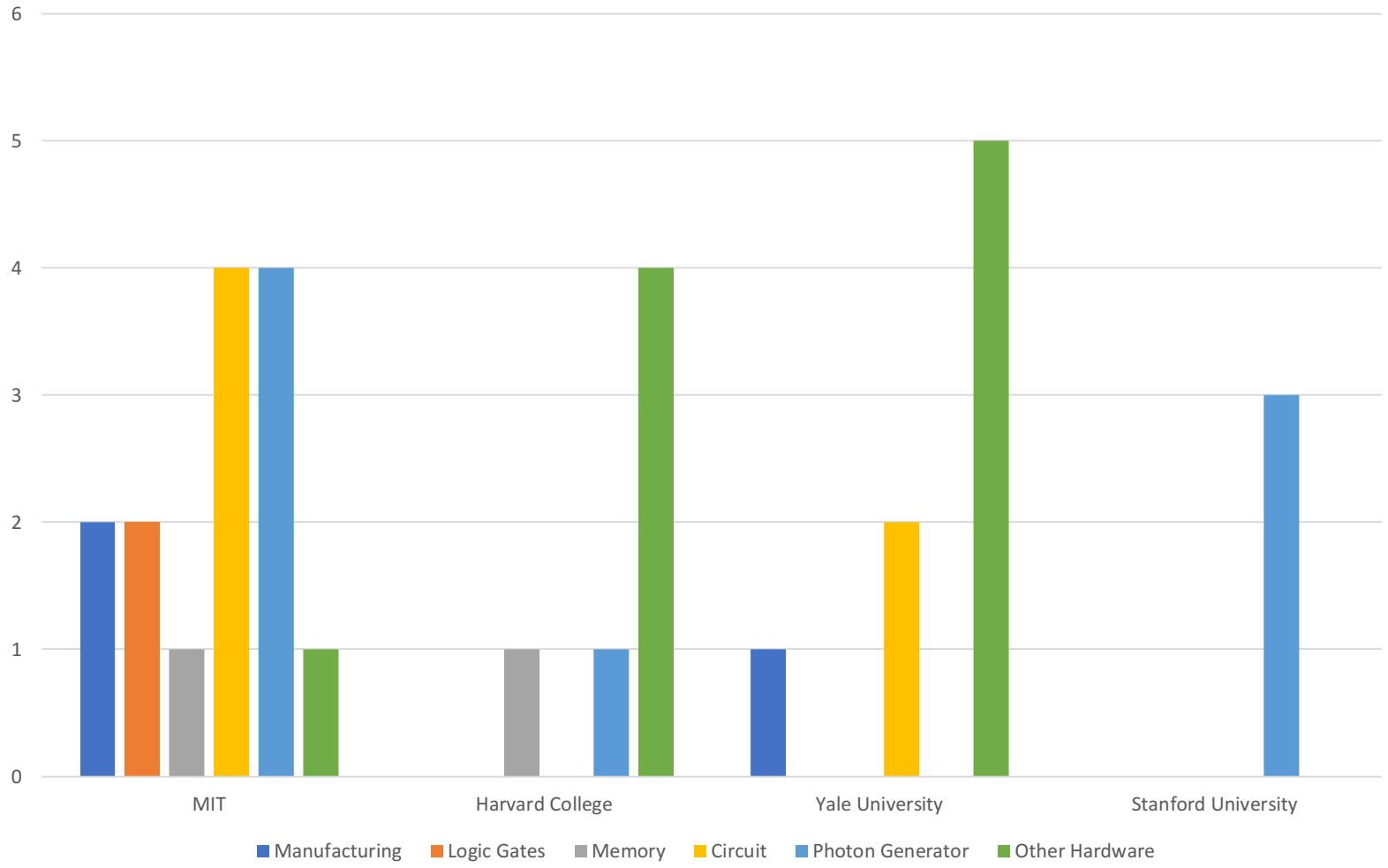
- Overall the collections of the top universities related to qubit technologies are small however it's clear that Yale is interested in super-conducting qubit technologies.
- Stanford has also done work in the quantum dot field.
- MIT has two patent families related to super-conducting technologies and one in quantum dots.
- Harvard also has one publication in quantum dots.



Note: Based on 12 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Academic Leader's Portfolio Breakdowns by Hardware Type

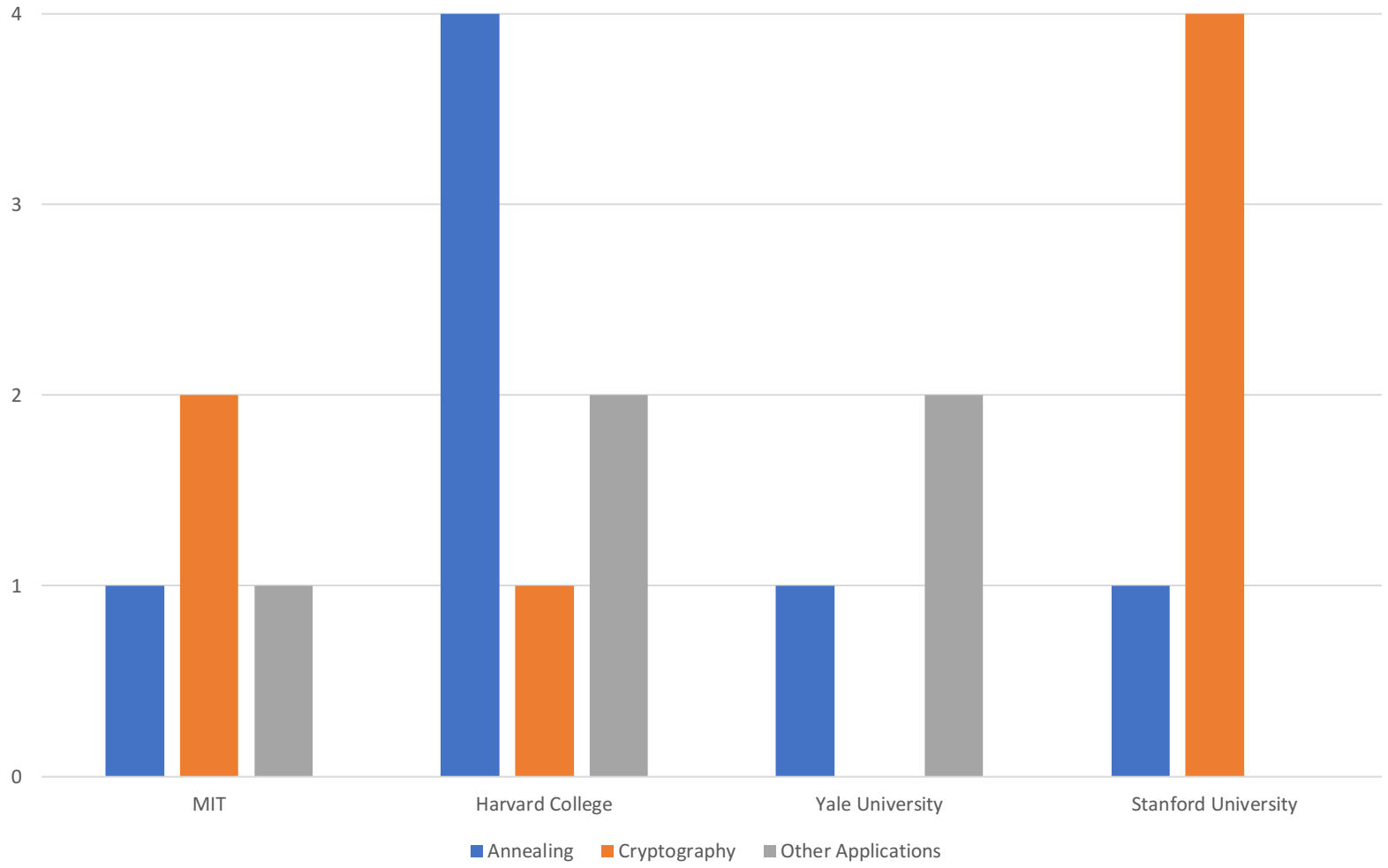
- While it appears that MIT's main interests under the hardware category are in circuits and photons they have done work in all of the fields.
- Harvard's work in Other Hardware is made up mainly of quantum processing devices while Yale's are related to amplifiers.
- Stanford's hardware publications are related to photons and photon generators.



Note: Based on 31 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Academic Leader's Portfolio Breakdowns by Application Type

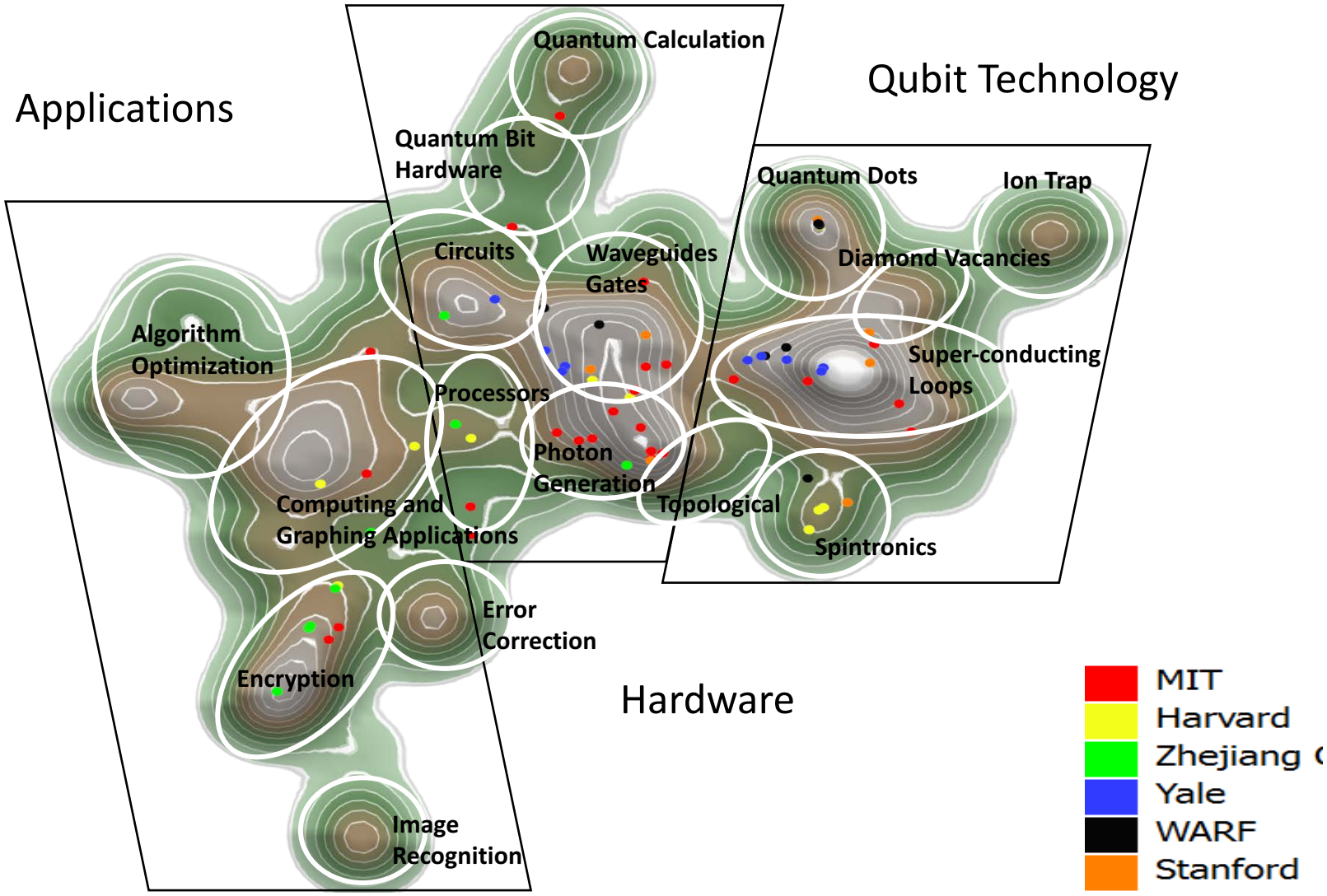
- The bulk majority of Stanford and MIT's publications in the application category are related to cryptography.
- All four universities have at least one document related to annealing and it is the main focus in Harvard's collection.



Note: Based on 19 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country. Documents can appear in more than one category.

Quantum Computing Patent Families Spatial Concept Map by Top Universities

- MIT has the greatest concentration of documents in the hardware category focused on photons and logic gates but they also have a solid grouping within super-conducting qubit technology. Only four publications are located in the application category.
- Yale, Stanford and WARF are all similarly distributed throughout the qubit technology category within superconducting loops, quantum dots and spintronics and the hardware category in logic gates, photons and circuits. None of them have any representation in the application category.
- Harvard has a small concentration in spintronics but most of their collection is spread across logic gates, processors and computing applications.
- Zhejiang is focused on encryption with sporadic distribution throughout the hardware category and has nothing in qubit technology.

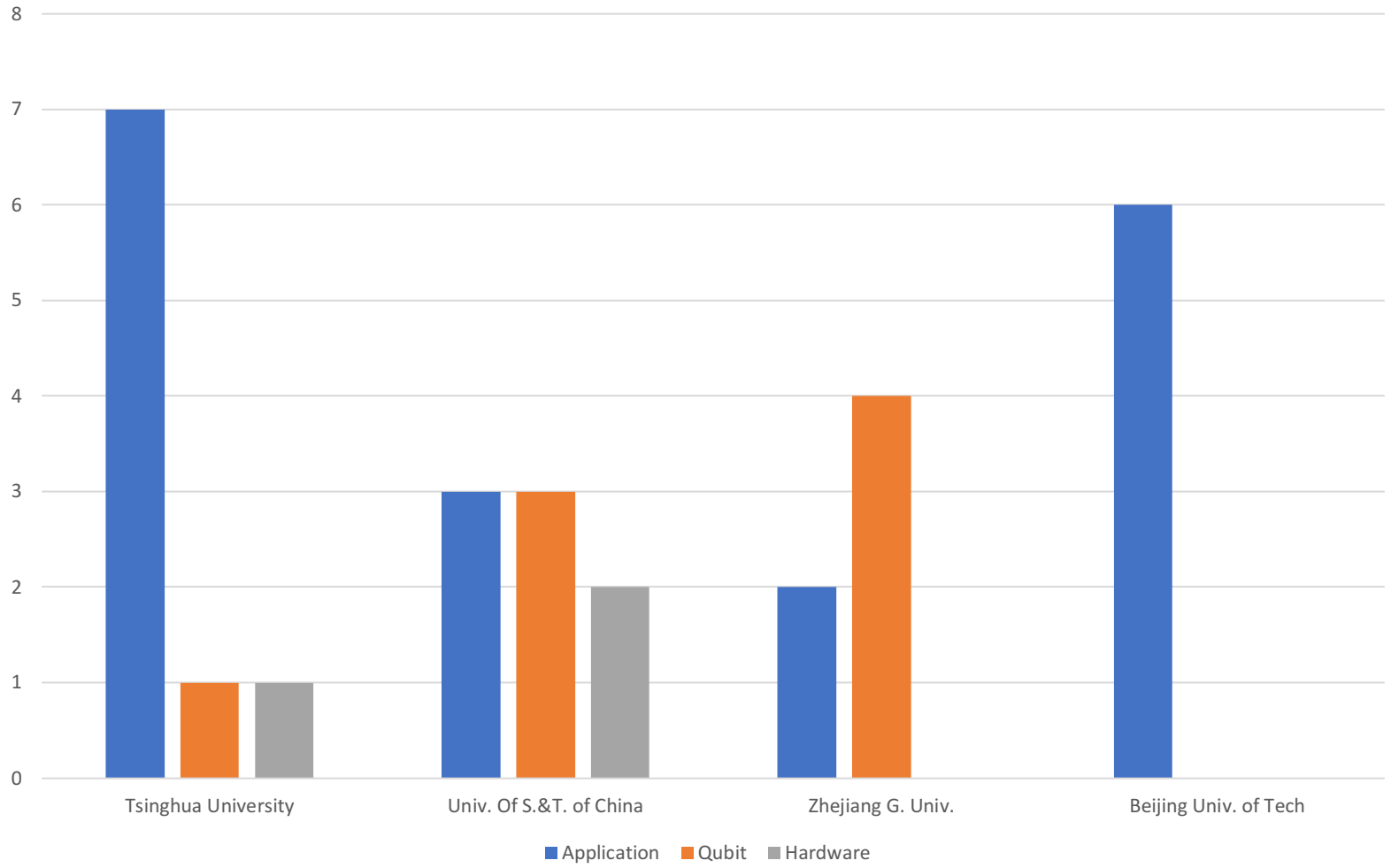


Note: Based on 56 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country.

Quantum Computing Chinese Universities Portfolio Breakdowns by Invention Category

- Unlike the Top American Universities, who are most interested in hardware and qubit technology, the top Chinese Universities have more patent families related to applications than both hardware and qubits combined.

- While qubit technology is the second largest invention category, it should be noted that none of these universities have any published work in specific qubit types, it's all general qubit reading and processing techniques.

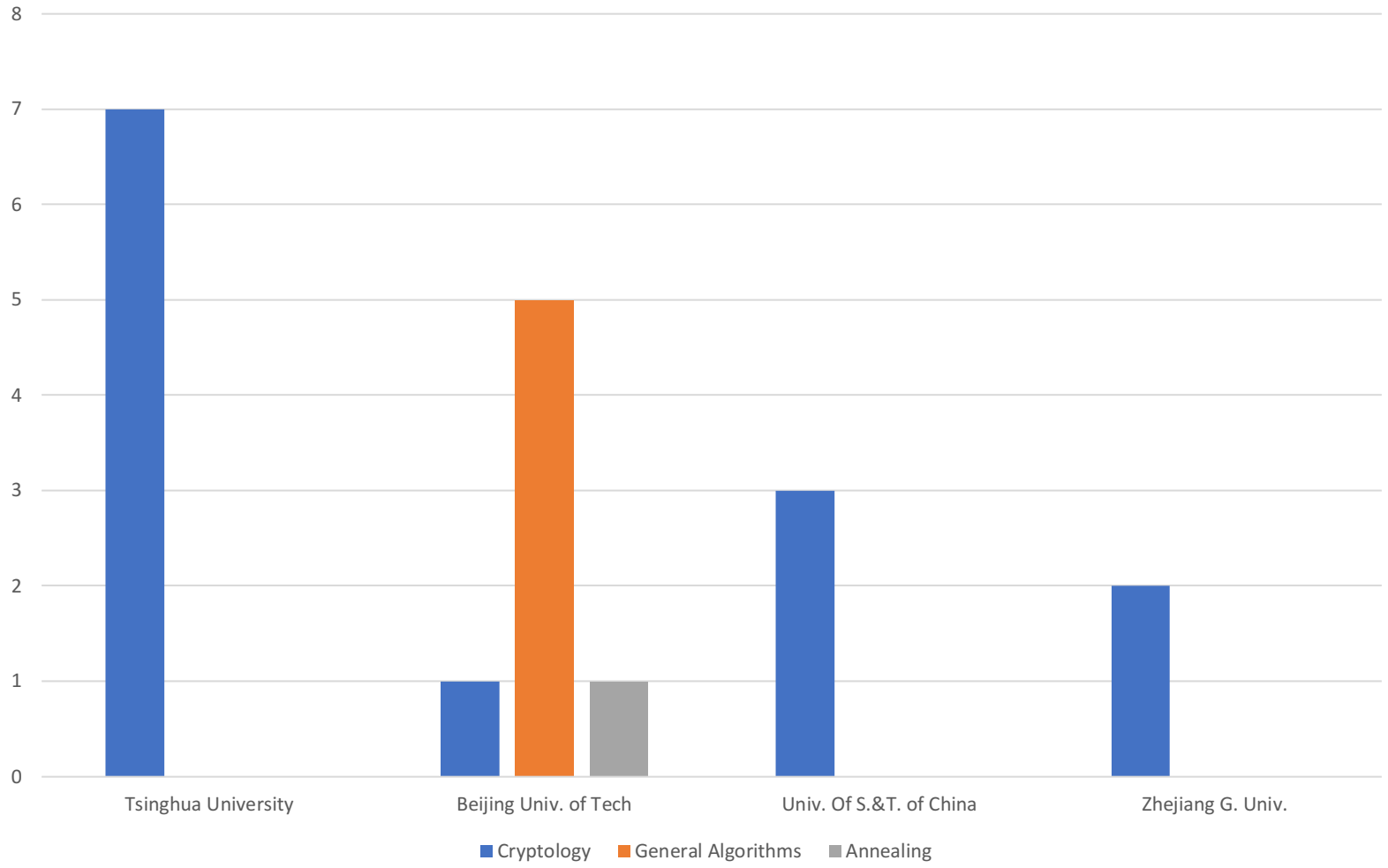


Note: Based on 35 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country. Documents can appear in more than one category.

Quantum Computing Chinese Universities Portfolio Breakdowns by Application Type

- The overwhelming majority of all the patent families that belong to the top Chinese Universities are related to quantum cryptology.

- Beijing University of Technology is the only one of the group with a focus on applications other than cryptology. They are working in general optimization algorithms and annealing.



Note: Based on 19 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country. Documents can appear in more than one category.

CITATION ANALYSIS FOR PRACTICAL QUANTUM COMPUTING

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Citation Analysis Notes

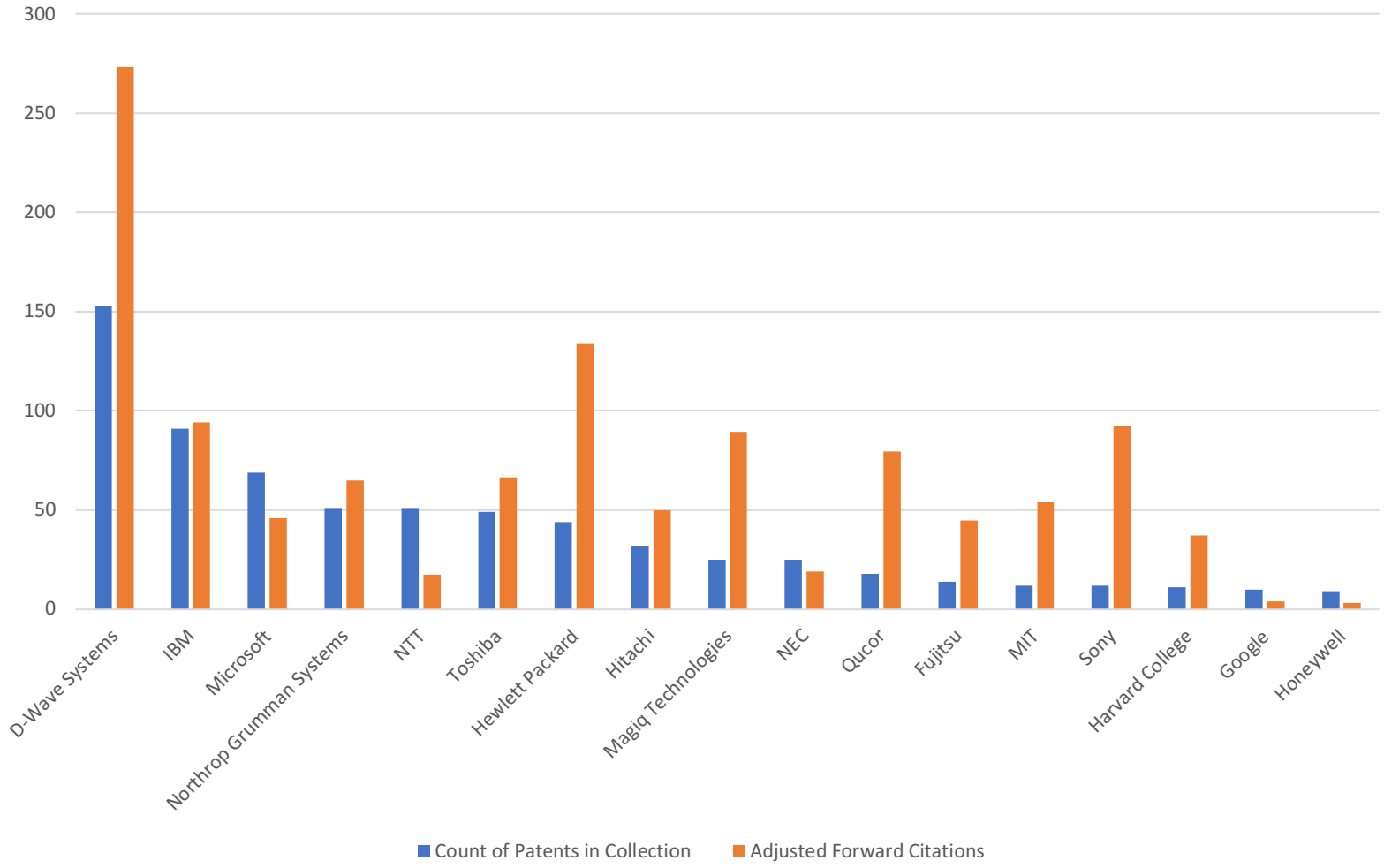
- Forward citations occur when newer patents cite details from older patents. Looking at forward citations is good way to determine the value of patents within a portfolio because a patent that is cited often is likely more useful and therefore more valuable than those that aren't.

- The Adjusted Forward Citations column is based on the number of forward citations in each companies portfolio adjusted for the size and age of the portfolio.

Note: Based on 1,455 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 206 documents for 2017.

Quantum Computing Industry Citation Analysis of Top Companies and Universities

- D-Wave Systems has the largest collection of patents and also a very high number of citations unlike NTT, Microsoft and IBM who also have large collections but a limited number of forward citations.
- HP has a very interesting portfolio based on its smaller size but high value of forward citations and also the fact that they are no longer showing an interest from a patenting perspective in this area. Qucor is similar to HP in this respect.

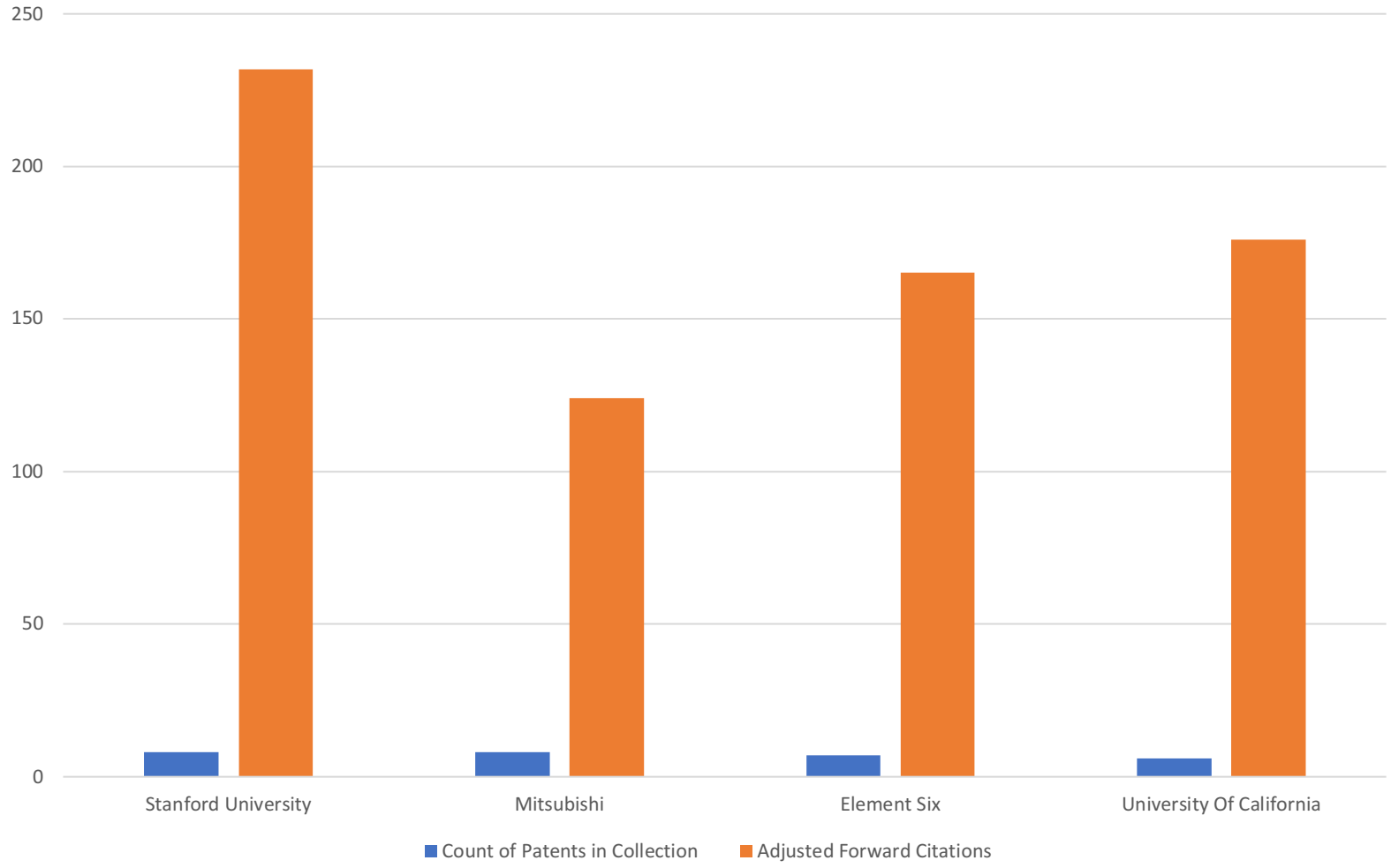


Note: Based on 676 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

Quantum Computing Industry Citation Analysis of Smaller Portfolios

- None of the collections for the owned by the organizations on the chart are larger than eight patent families which illustrates the value of those patent families based on the number of forward citations.

- It should be noted that the majority of the citations of Element Six's portfolio are not related to quantum computing applications but are for other uses of synthetic diamond.

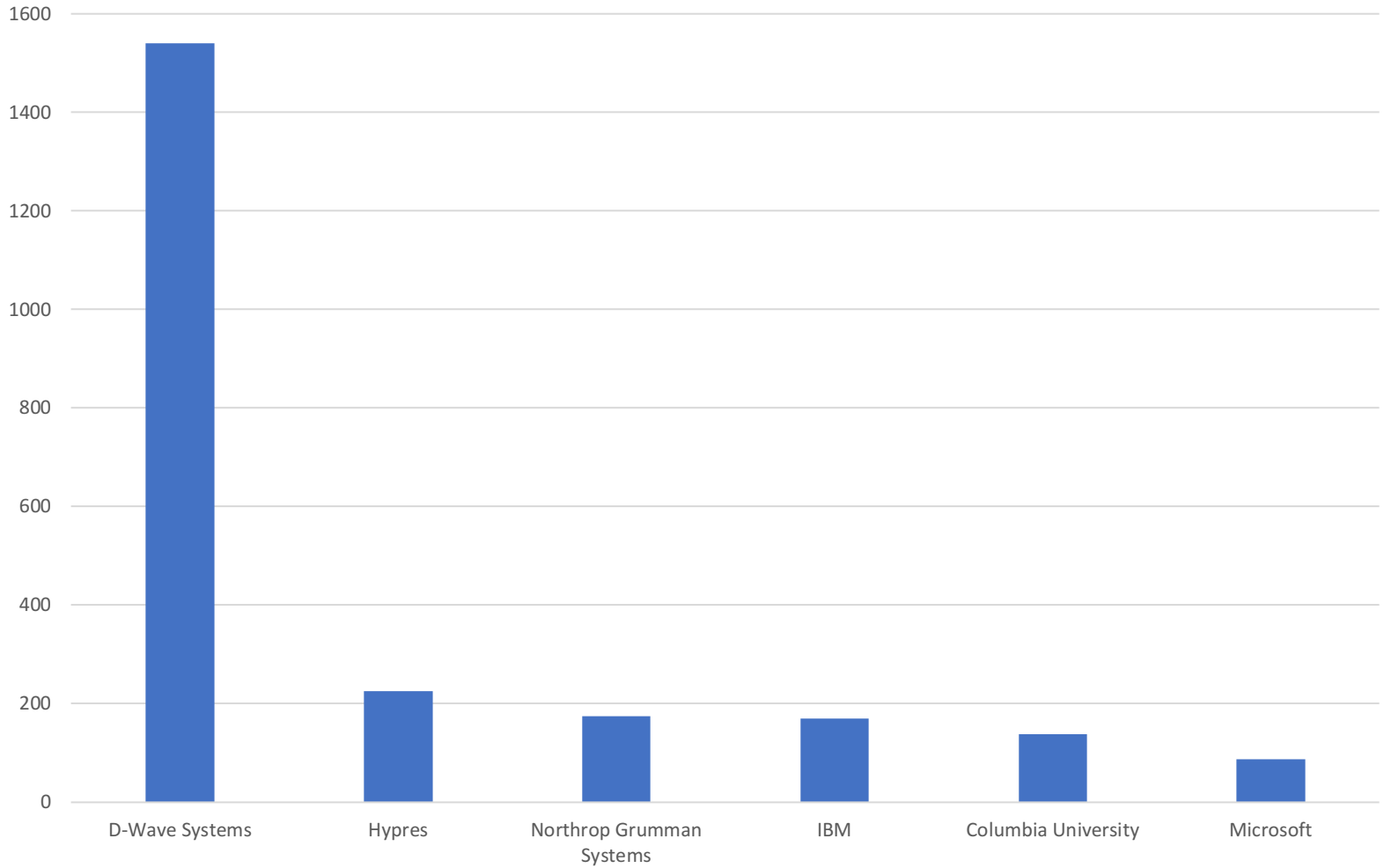


Note: Based on 73 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

D-Wave Systems Forward Citations by Top Citing Organizations

- Due to the size and age of D-Wave Systems quantum computing portfolio it is no surprise they have 2,942 forward citations, a number five times greater than IBM, the second largest company collection. However over 50% of D-Wave's citations are self-cites, making their total number of citations slightly less impressive.

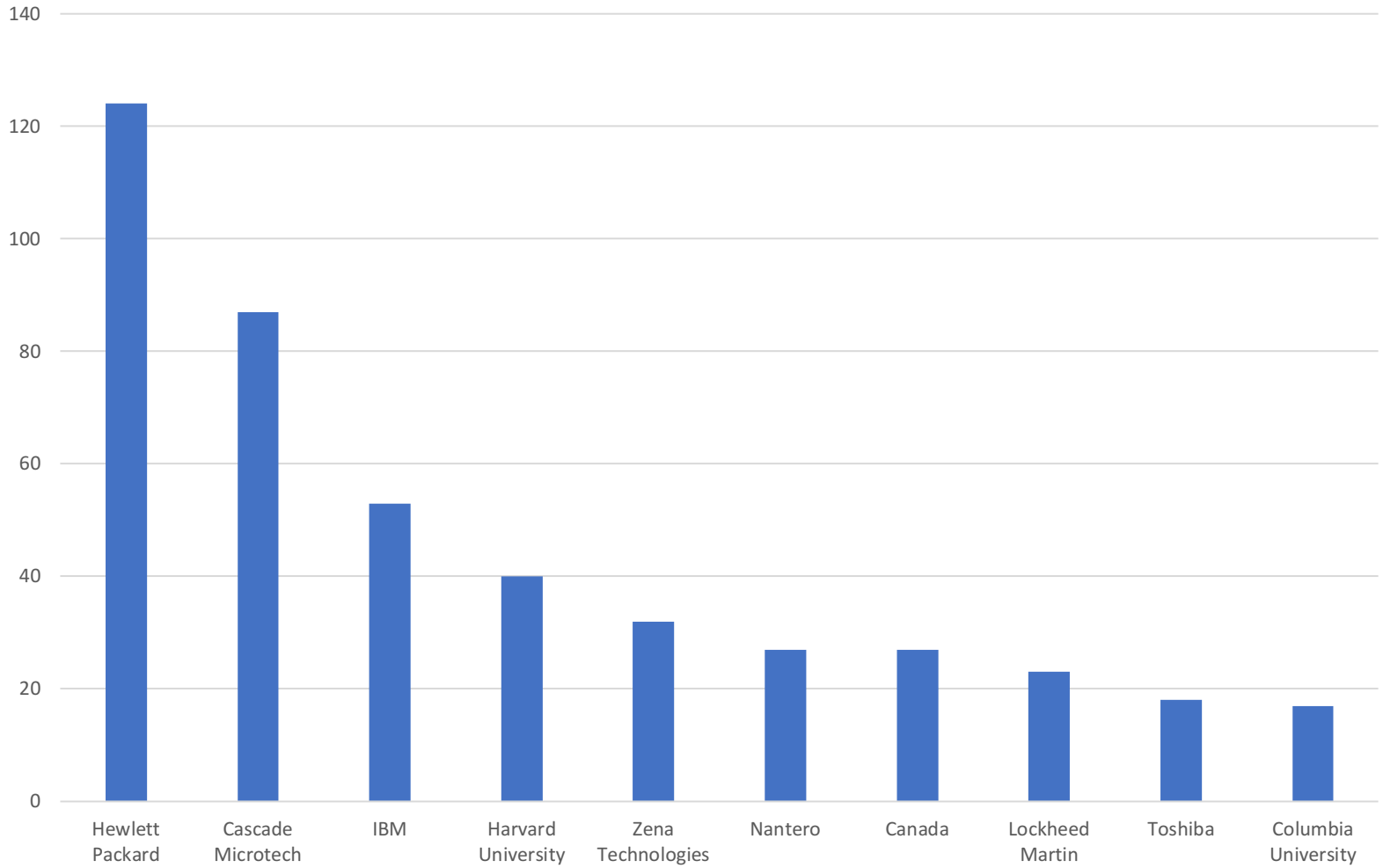
- Hypres tops the list, as the first outside company, with the most forward citations of D-Wave's portfolio and is a private company that has not been discussed yet. They specialize in the development and commercialization of superconducting microelectronics. Hypres has five patent families directly related to quantum computing with publication dates ranging from 2008 to 2016 and they deal almost entirely with the systems and methods for building super-conducting circuits.



Note: Based on 2,336 forward citation patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

Hewlett Packard Forward Citations by Top Citing Organizations

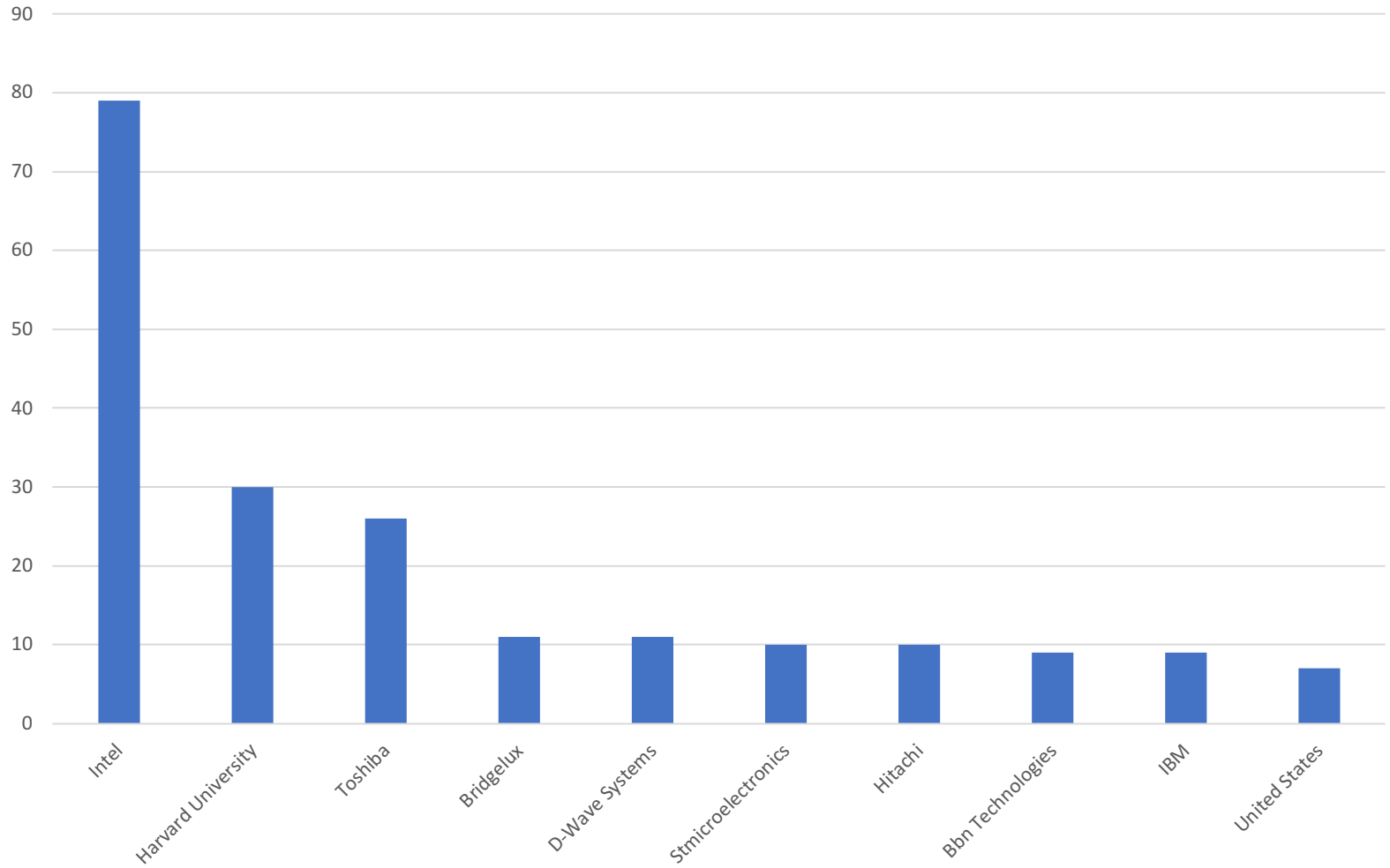
- Similar to D-Wave, HP also has the most forward citations of their collection, however their number of self cites only accounts for approximately 15% of all forward citations unlike D-Wave where they are over 50%.
- Cascade Microtech, a semiconductor manufacturing company, comes in as the top non-HP company. However all of their citations come from one document in HP's collection (US7002133B2) which is related to a photon detection system.
- Unlike Cascade Microtech, IBM cites 18 different publications in HP's portfolio which is over 40% of their entire collection. Based on the perceived value of HP's portfolio due to the large number of forward citations and their lack of interest in quantum computing in recent years, this would be a good target as a possible partnership or acquisition for IBM.



Note: Based on 448 forward citation patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

Stanford University Forward Citations by Top Citing Organizations

- Stanford University only has eight patent families in the quantum computing field yet they have 308 forward citations. They also only have five self cites which a ratio much smaller than most other entities with large numbers of forward citations.
- Intel has more than 2.5 times more forward citations of Stanford's portfolio than Harvard.
- It should be noted that 179 of their 308 forward citations come from one publication (US7385262B2), including all 79 of Intel's cites, and that publication was expired on 6/10/2016 due to failure to pay the maintenance fee.



Note: Based on 202 forward citation patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country;

GOVERNMENT INTEREST DISCUSSION ON PRACTICAL QUANTUM COMPUTING

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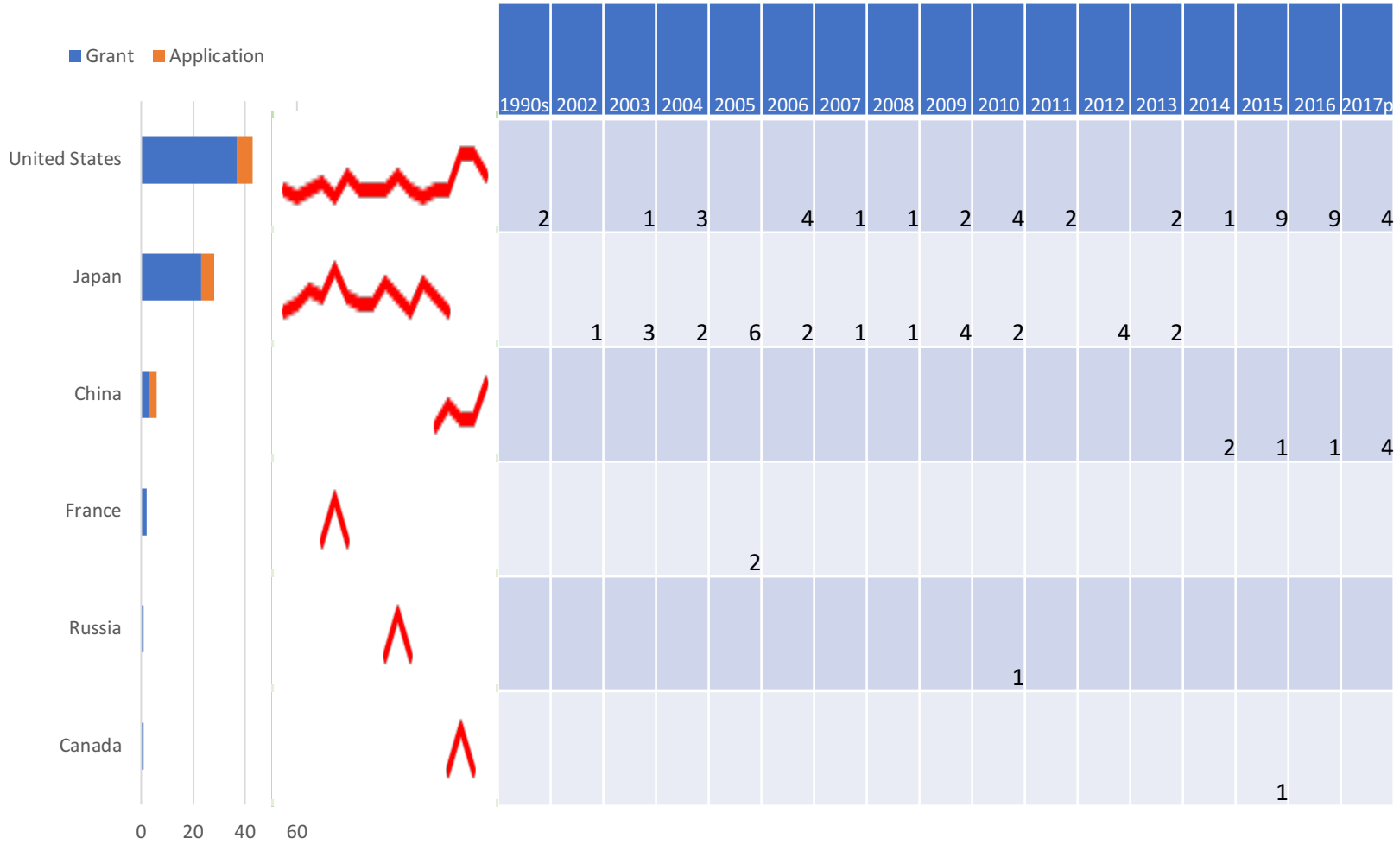
• Quantum Computing Patent Families by Governments

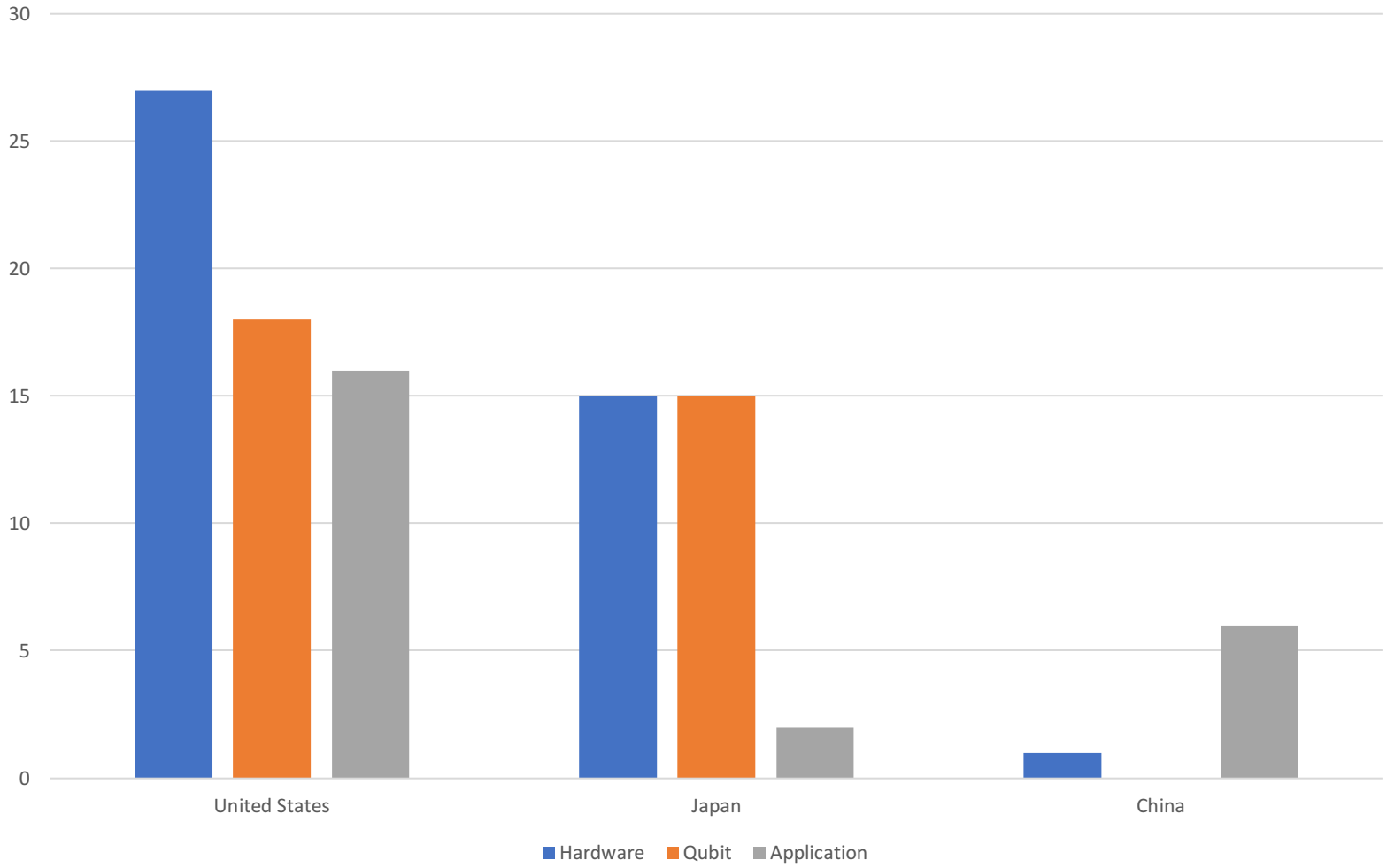
- The United States is the clear leader from a patenting perspective in quantum computing, especially in recent years publishing 20 documents since 2015.
- Japan has the second largest portfolio by a significant margin, however they have not seen anything published since 2013.
- China is new to the field with all six of their patent families coming since 2014.



Note: Based on 81 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Currently 4 documents for 2017.

Quantum Computing Patent Families by Government and Invention Category

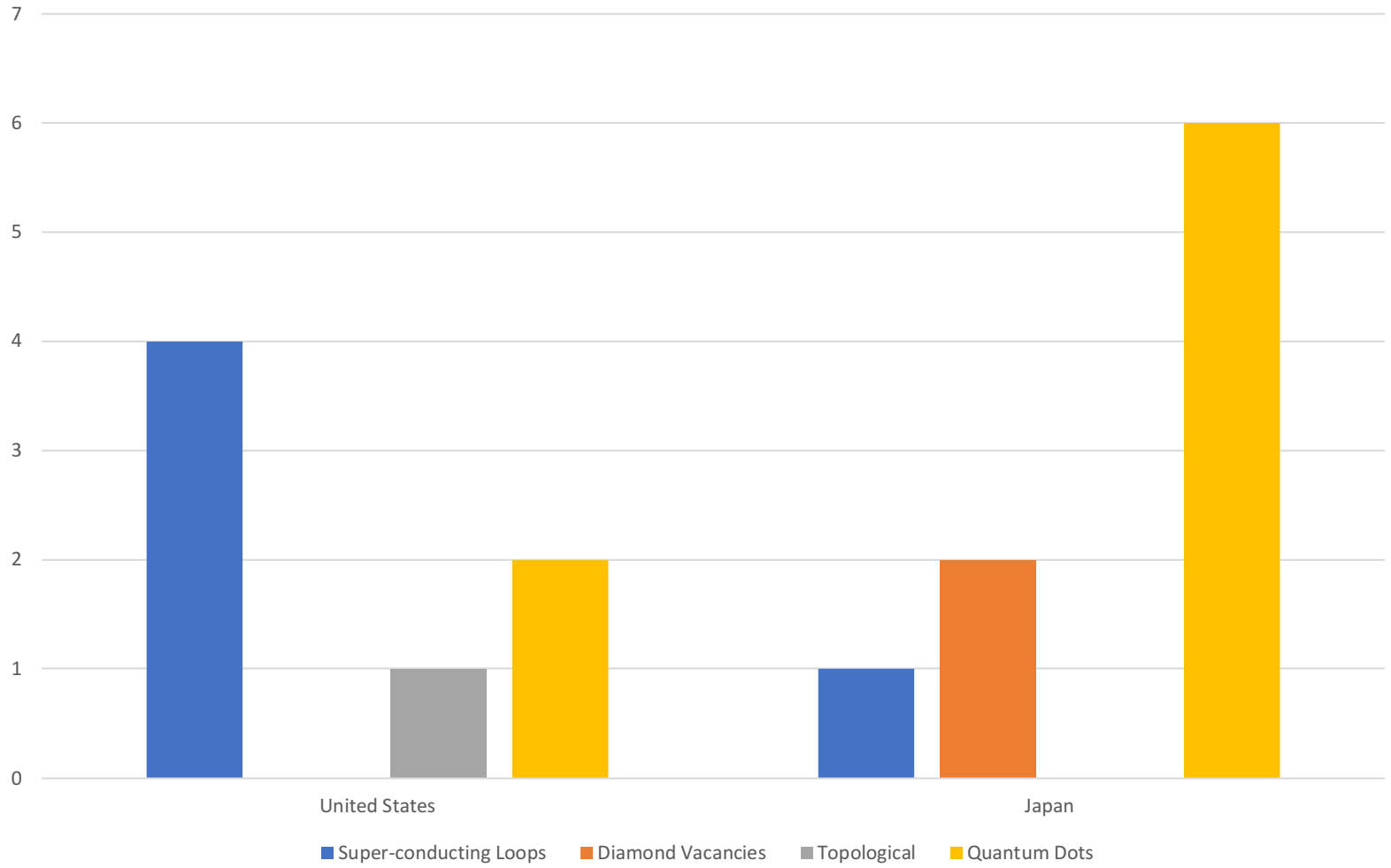
- The United States inventions are relatively evenly distributed across all three categories with slightly more focus in Hardware.
- Japan's collection is centered around both Hardware and Qubit Technologies with little interest in applications.
- While China's collection is currently significantly smaller than both the U.S. and Japan, it's clear their focus is on Applications.



Note: Based on 100 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Patent Families by Government and Qubit Type

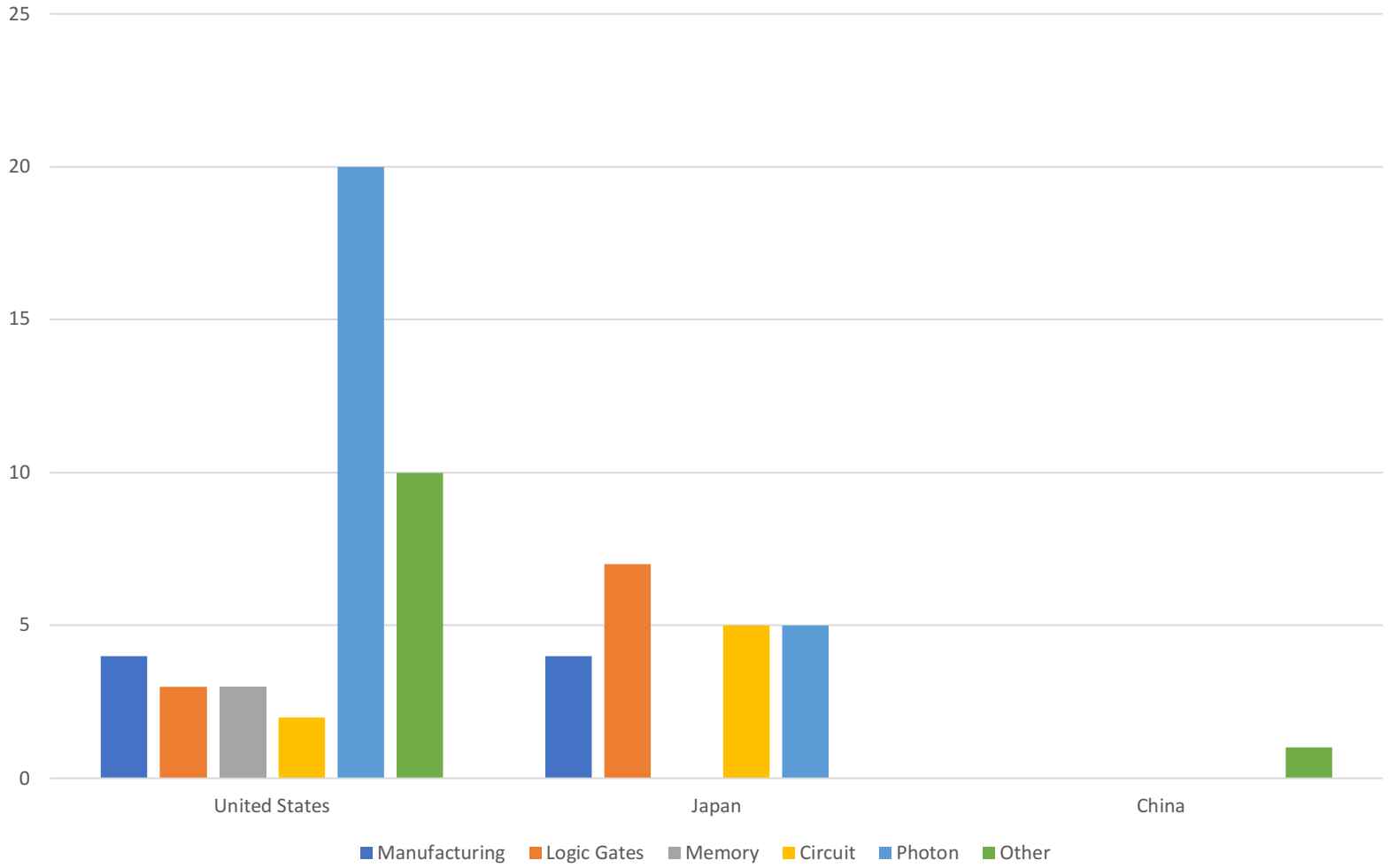
- In Qubit Technology, the United States is most interested in super-conducting qubits followed by quantum dots and one document related to topological qubits.
- Japan is clearly focused on quantum dot technologies.
- China does not have any patent families in the Qubit Technology category.



Note: Based on 16 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Quantum Computing Patent Families by Government and Hardware Type

- The United States has twice as many patent families that deal with photons and photon generators than the second largest hardware field which shows a clear interest in that area. However they also have a multiple publications in all six of the hardware fields. The Other Hardware sub-category is made up primarily of documents related to generic quantum computing devices and data transfer systems.
- Japan's hardware portfolio is evenly distributed across circuits, photons logic gates and manufacturing techniques.
- China has one document related to an error-correction system.



Note: Based on 64 Quantum Computing patent documents from a worldwide search in Thomson Innovation; limited to one document per family, based on DWPI with US as primary country; Documents can appear in more than one category.

Collection methodology

- Searching was conducted in worldwide patent documents in Derwent Innovation for the following concepts:
  - IPC / CPC classes specific to quantum computing or nano-technology for information processing
  - For the concepts of quantum computer(s) or processor(s), or qubit(s) in the Titles, Abstracts, or Claims
- Collection was limited to one document per family using DWPI families
  - The US was retained as the primary country
- Categorization based on manual review was conducted for these families based on the major categories and sub-categories
- Assignee names were standardized based on known mergers, acquisitions, and change of ownership

Acknowledgements

- Patinformatics would like to thank the following organizations for the use of data, or tools for the development of this study:

  - Clarivate Analytics — Derwent Innovation was used for searching, and for reviewing patent records for categorization and relevance

  - Evaluserve — the KMX Patent Analytics package was used for the creation of the spatial concept maps

  - The majority of the charts, and graphs used in this study were generated using Microsoft Excel

The Analysts

Bryan Scanlon attended Ohio State University where he majored in finance. After Ohio State, Bryan accepted a consulting role at Accenture where he spent time working with AT&T on a number of projects including data analytics work. Now he works with Patinformatics in an analyst role helping clients drive business insights from intellectual property data.

Anthony (Tony) Trippe is Managing Director of Patinformatics, LLC. Patinformatics is an advisory firm specializing in patent analytics and landscaping to support decision making for technology based businesses. In addition to operating Patinformatics, Mr. Trippe is also an Adjunct Professor of IP Management and Markets at Illinois Institute of Technology teaching a course on patent analysis, and landscapes for strategic decision making.

Gargi Mishra is an Intellectual Property Professional with over 3 years of experience in India. She has an Engineering Master's degree in "Sensor Systems Technology" and a Bachelor's in "Electronics & Communication". Gargi earned her Master's in Intellectual Property Management & Markets from Illinois Institute of Technology in 2017.

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