The Canadian QUANTUM ECOSYSTEM REPORT 2023

QAI QUANTUM ALGORITHMS INSTITUTE

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Forward

The Quantum Algorithms Institute in British Columbia, Canada, has a mandate to support the economic growth of the world class quantum computing cluster in BC and across Canada.

Most of the expertise on quantum physics and quantum technologies is still held by academics, professors, post–graduate and graduate students in universities, colleges and research institutions. However, since 2015, the world has seen an explosion of interest in quantum technologies, including increasing government support and business investment[1].

On the ground in Canada, the transition of quantum experts out of academia and into startup companies is accelerating, reflecting the swift growth in the commercialization of quantum technologies.

To gain a better understanding of what is happening in Canada's rapidly changing quantum sector and the dynamic nature of the quantum talent pool in Canada and around the world, QAI commissioned a ground–up exploration of Canada's quantum ecosystem. This report focuses on analysis of national and international patent filings, non-peer-reviewed publications in the arXiv.org database, and self–reported data gleaned from users of social media [2].

Our analysis captures a real-time perspective on the transition to commercialize quantum technologies.

Although the data sources for this analysis are noisy, the data sets they yield can be rapidly searched and parsed and are large enough to identify trends that would otherwise be invisible. For example, from social media, one can identify groups of people who volunteer that they are working on quantum in academia and in business. The Canadian government's latest National Occupational Codes (from 2021) list more than 40,000 job titles; none of them contain the word quantum. Although Canada's government statisticians will count quantum experts among Canada's researchers, physicists, engineers, and computer scientists, this analysis must look to unconventional sources to isolate today's quantum sector and track its development.

This ecosystem analysis uses data available in December 2022 and January 2023, to illuminate and quantify some aspects of research and commercial activity and the workforce in Canada's quantum sector.

This report has been created as an interactive online document. In the online version, the Figures are interactive and can be explored to highlight attributes by, for example, year or country. Readers can also download a static PDF of the report.

Louise Turner
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Surrey, British Columbia,
June 2023

Key Research Findings

Innovation in Quantum

Canada's Business Ecosystem for Quantum

Canada's commercial quantum ecosystem is made up of 55 home-grown companies employing more than 1,000 people. Between them, these companies hold 570 patents and have received more than $750 Million in financing. In addition to these Canadian companies, thirty international enterprises with quantum businesses or business groups also operate in Canada.

Academic Research

The global quantum research community is vibrant. Analysis of the arXiv.org 1 dataset shows global interest in quantum physics research with contributions from countries on all continents since 2016. The United States and China remain top contributors, with the latter experiencing growth in author numbers. In Canada, Alberta, British Columbia, Ontario, and Quebec are leading provinces in quantum physics research, with the Perimeter Institute being the most significant single contributing institution.

Global Collaboration

International collaboration is a key feature of quantum physics research, with almost 90% of papers being collaborations. These associations are not limited by political or economic lines: the quantum physics field is more open compared to other high-tech fields. The United States and Europe are prominent players, with strong connections to each other and other countries. China operates in a more closed ecosystem. In Canada, the main collaboration poles are with the United States and the Germany-Switzerland-Italy corridor. Authors from every country represented in arXiv have collaborated with a Canadian author at least once since 2016.

Patents

The last 10 years have seen an explosion in the number of quantum patent applications to Canada's Patent Office from companies around the world. At the same time, the number of patents granted is increasingly falling behind the number patent applications. From these data it is possible to observe the growth in competition through patent filings, signs of companies preparing the market for maturing products, as well as the increasing global competition for quantum talent.

The Global Competition for Quantum Talent

Quantum Talent

It is necessary to look to unconventional data sources to identify today's quantum workforce and track its development. Based on self-reported social media data, it is possible to see that most quantum-related fields are still firmly rooted in the world of academic research. Some groups of quantum experts are showing signs of transitioning into market-ready fields, with a growing percentage of quantum workers moving to commercial software or hardware roles. This rapid movement of talent from research to industry is putting pressure on an already tight pool of quantum talent.

Talent Flow

Quantum talent is globally in high demand, and Canada is among the leading countries when it comes to attracting and retaining quantum experts. Each year, Canadian academic institutions attract quantum students and researchers from around the world. This helps to explain why Canada has one of the best publication impacts per capita. However, Canada has a net loss of quantum talent, with a negative net talent flow with the United States and some other larger ecosystems such as Europe and China.

Notes on Methodology

To gain a better understanding of what is happening in Canada's rapidly changing quantum sector and the dynamic nature of the quantum talent pool in Canada and around the world, QAI commissioned a ground-up exploration of Canada's quantum ecosystem. This research focuses on analysis of national and international patent filings, non-peer-reviewed publications in the arXiv.org database and self–reported data gleaned from users of social media.

This analysis captures a real–time perspective on the transition of quantum technologies from academia to the commercial sector more rapidly than with any other disruptive technology. The need to use alternative data sources is a reflection of the speed of this transition. This research brings to light both the challenges and opportunities for Canada's quantum ecosystem.

This report aims to capture a snapshot of the state of Canada's quantum ecosystem, with special emphasis on quantum computing, at the start of 2023.

This means two things:

1. **Methodological choices were made with velocity in mind:** when a decision had to be made between precision and scope, scope was chosen. For example, the social media approach can only point to talent trends and not to specific numbers in specific places.

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2. **Choices were made to have a more holistic understanding of the ecosystem rather than having vertical specificity.** c. For example, rather than only targeting journal-published papers, this analysis uses papers published on arXiv. arXiv is a database of pre-published papers which is used as a staging ground for peer-review of papers for academia, as well as for conference presentations for the business world, where the database is used to preview cutting-edge research before it is announced to the wider public.

As with any methodological choices, these decisions come with limitations. In the case of this report, a choice was made to prioritise data to facilitate a large scope faster, at the cost of granular precision.

A Brief Business Overview of Quantum

Quantum Computing is a disruptive technology that will enable us to apply computation and analysis to topics that are out of reach using today's most powerful, classical supercomputers.

Quantum Computing is a disruptive technology that will enable us to apply computation and analysis to topics that are out of reach using today's most powerful, classical supercomputers [3].Quantum computers are best suited to optimization, simulation, machine learning and cryptographic problems [4]. While quantum technology will not be available – or needed – on desktop computers, laptops or smartphones, cloud-based quantum services will be widely used in business, academia, and government to:

- optimize the operation of complex systems such as power grids or transport systems, improving efficiencies, minimizing energy usage, and reducing the emission of greenhouse gases[5];
- simulate complex multi-dimensional systems such as the climate and oceans;
- model complex processes such as nitrogen fixation in agriculture and insulin creation to understand and treat diabetes[6];
- improve portfolio and fund management in the financial sector[7];
- discover new molecules with applications in drug development, advanced materials development, and eco-friendly processes such as recycling plastics and removing carbon dioxide from the atmosphere;
- accelerate and advance machine learning processes such as the early identification of malignant growths from ultrasound, MRI or CAT scans; and,
- develop new and hack-proof networking and communications channels to counter cybersecurity attacks.

The development of quantum computing and networking technologies has been accelerating rapidly, with significant strides being made since the turn of the 21st century.

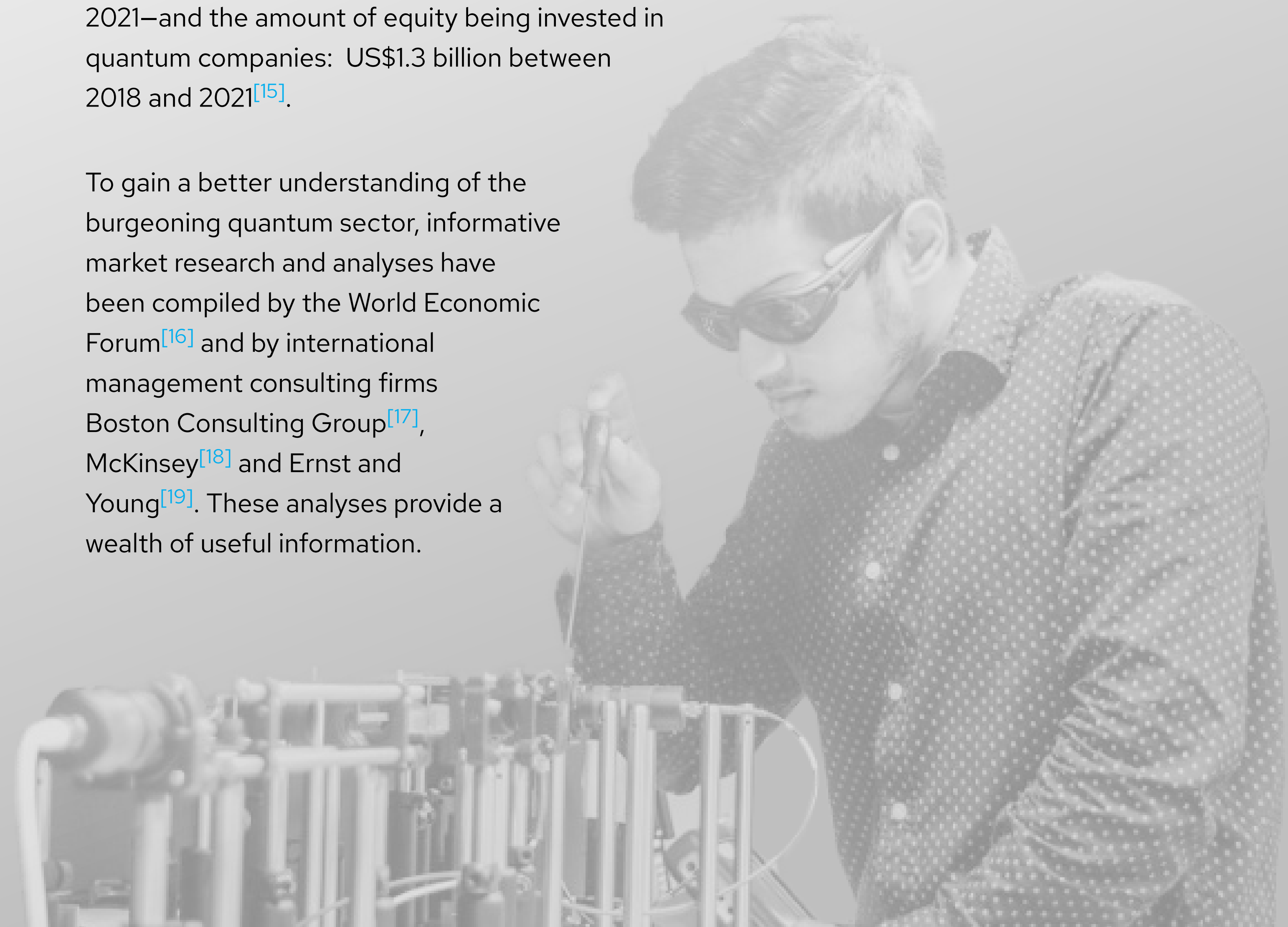
Much of the expertise in quantum still resides in universities[8], but increasingly quantum computing software, hardware, and networking companies are spinning out of universities and into the commercial world, while the world's largest computing and social media companies (IBM, Google, Microsoft, AliBaba, Baidu, Amazon) continue to work on quantum hardware and solutions.

Milestones such as the launch of D-Wave's annealing computer in 2011[9], the founding of 1QBit– the world's first quantum software company – in 2012[10], IBM making its quantum computers accessible through the IBM Cloud in 2016[11] , as well as demonstrations of Quantum Supremacy by Google (2019), the University of Science and Technology of China in Jiuzhang (2020)[12], and Xanadu (2022)[13] are indicative of the technological advances that are bringing commercial scale, fault tolerant quantum computing closer to commercial reality.

These technological advances are both a reflection and a result of increasing investment in quantum research in the last twenty years, and the development of national quantum programs and strategies by at least 15 countries since 2016[14].

Growing business interest in quantum computing is reflected in the rapid growth in the number of quantum computing companies in the world—up from 42 in 2015 to 195 in 2021—and the amount of equity being invested in quantum companies: US$1.3 billion between 2018 and 2021[15].

To gain a better understanding of the burgeoning quantum sector, informative market research and analyses have been compiled by the World Economic Forum[16] and by international management consulting firms Boston Consulting Group[17], McKinsey[18] and Ernst and Young[19]. These analyses provide a wealth of useful information.

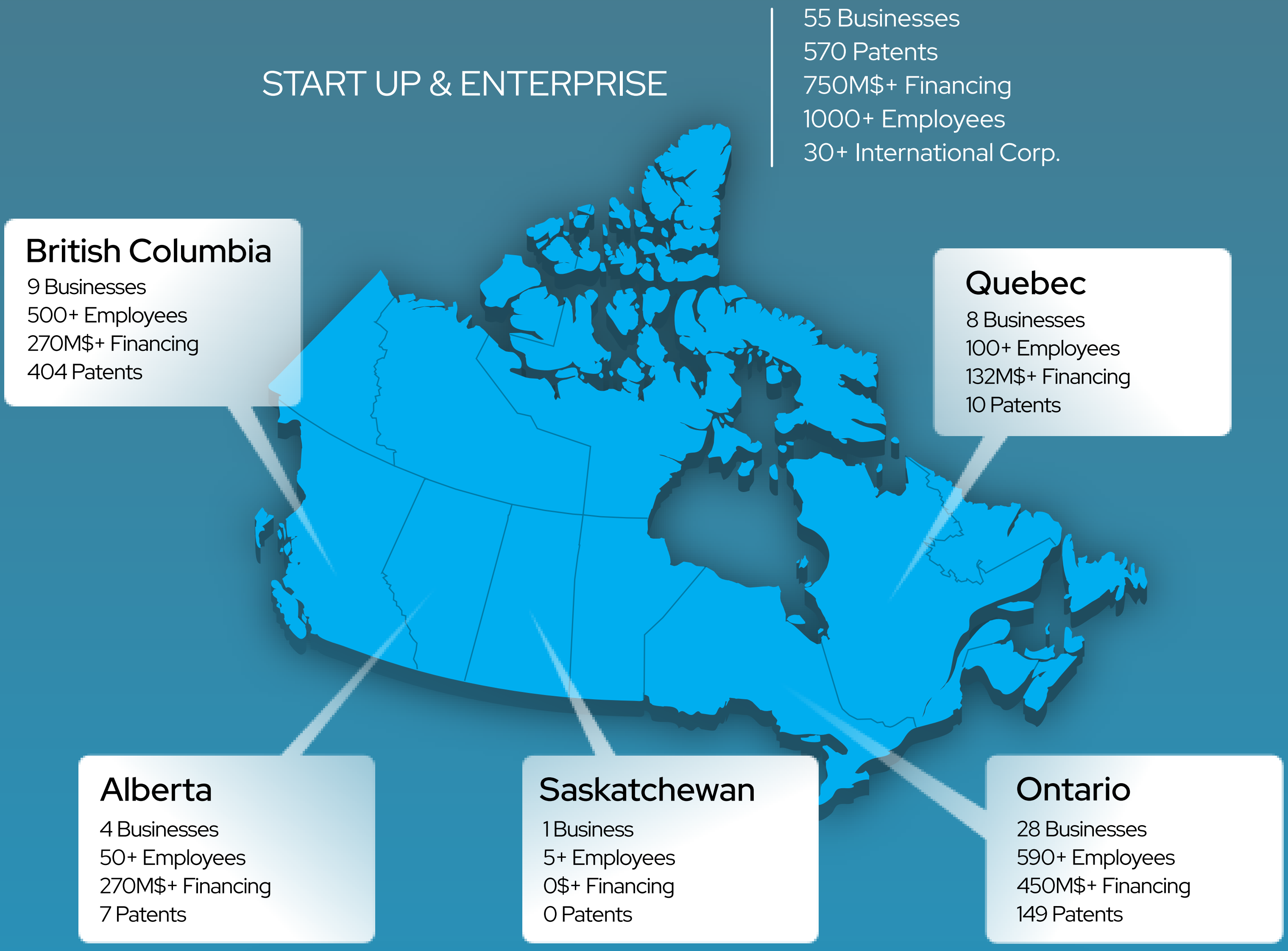


The Quantum Ecosystem in Canada

Since the granting of the first quantum technology–related patent at the Canadian patent office in the seventies, the Canadian quantum ecosystem has been one of the most vibrant and innovative in the world.

Canada was a significant investor in early research programs focusing on quantum technologies and quantum computing, including and investment of $1 billion in quantum research from 2009 to 2020[20]. As one of the world's leading nations in quantum research, Canada ranked 5th in the G7 in total expenditure on quantum science and 1st per capita[21].

In 2011, D-Wave Systems (founded in British Columbia, in 1999) launched the world's first commercially available quantum computer. In 2012, 1QB Information Technologies (1QBit), the world's first dedicated quantum computing software company, was also founded in BC[22].



Based on publicly available information found on social media, Crunchbase, Pitchbook and Quantum Industry Canada

Figure 1. Map of Canadian–grown Quantum Businesses

A 2023 review of online information conducted as part of this Quantum Algorithms Institute analysis showed that today, Canada's commercial quantum ecosystem is made up of 55 home-grown companies employing more than 1,000 people. Between them, these companies hold 570 patents and have received more than $750 Million in financing. In addition to these Canadian companies, thirty international enterprises withtum businesses or business groups also operate in Canada.

Patents and Competition for Knowledge

Methodology and Caveats

While quantum technologies are mostly covered by the international patent classification system, it was found that many other technologies share similar vocabulary. For example, many quantum keywords were found to overlap with medical patent keywords, as well as with the vocabulary used in many hardware patents related to computer screens. To capture these false positives, Bert Topic was used to cluster patents by keywords used in the description of the patents.

Patents and Competition for Knowledge: Data and Analysis

Patent applications are often submitted to more than one patent office at a time to maximize the chances of securing protection of the applicant's intellectual property. Figure 2 shows the number of quantum–related patent applications filed by country for the period from 2015 to 2022. The Chinese and American markets are the primary targets of companies' patent strategies. While most quantum technology patents are applied for in both countries at once it is worth noting that there are some notable exceptions to this trend. Specifically, the American Patent Office tends to receive significantly more submissions related to machine learning, hardware, and computing than its Chinese counterpart.

It is also worth mentioning the role of the World Intellectual Property Organization (WIPO) in the global patent landscape. Although WIPO does not grant patents, its international patent application system allows applicants to simultaneously seek protection in multiple countries. In recent years, the number of quantum patent submissions through WIPO has been steadily increasing, indicating a growing interest among assignees in pursuing multinational patent protection. This may reflect companies' expanding global market strategies.

In addition to the Chinese and American markets, other major players in the patent landscape include the European, Japanese, and South Korean patent offices. These offices receive similar numbers of patent submissions, suggesting that companies are taking a relatively balanced approach to targeting these markets.

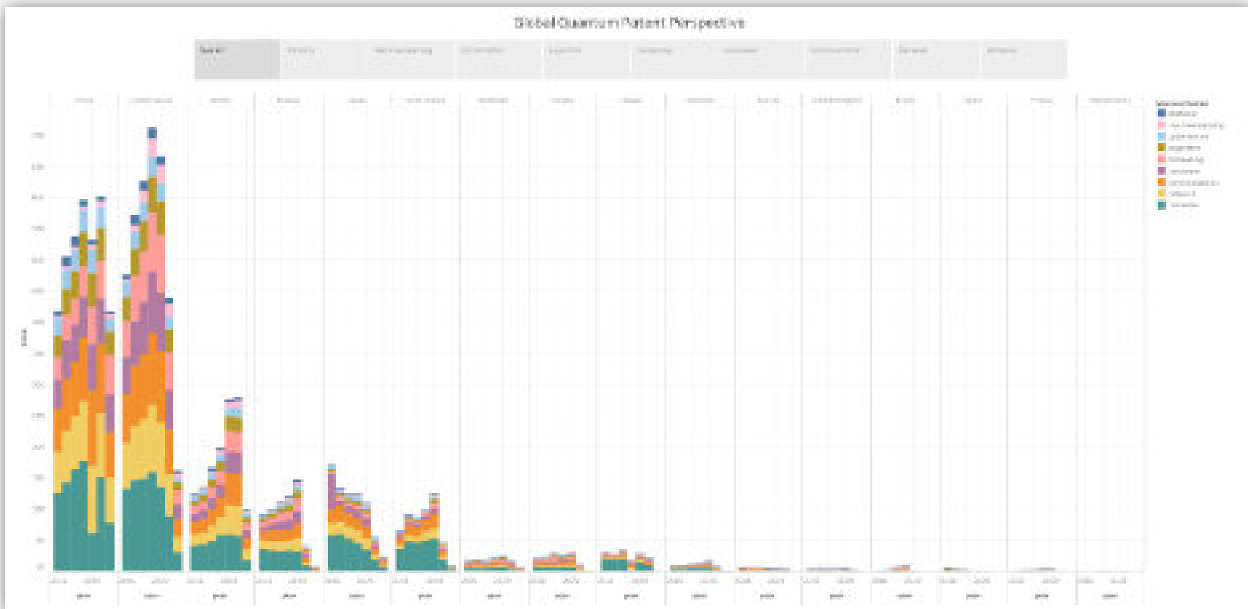


Figure 2. Global Quantum Patents filed in National Patent Offices, 2015 to 2020

An analysis of the patent applications filed in the Canadian Patent Office reveals that a significant portion of quantum technology patents were filed by assignees with headquarters outside Canada. A total of 1,204 different assignees with headquarters mainly located abroad have filed patent applications in the Canadian Patent Office.

Since the 1970s, a total of 3,594 patent applications related to quantum technology have been filed in Canada, half of them since 2013. Despite the increasing volume of patent filings in Canada, the patent granting process is still lengthy: of these 3,594 patent applications filed, only 1,320 have been granted to date. The average wait time for patent grants in Canada is around 6 years.

Further research on the 150 most active assignees, shown in Figure 3, reveals that they originate from at least 13 different countries, with the majority coming from the United States and Western Europe. This shows that the Canadian patent system is an attractive option for companies from a variety of different countries looking to protect their intellectual property.

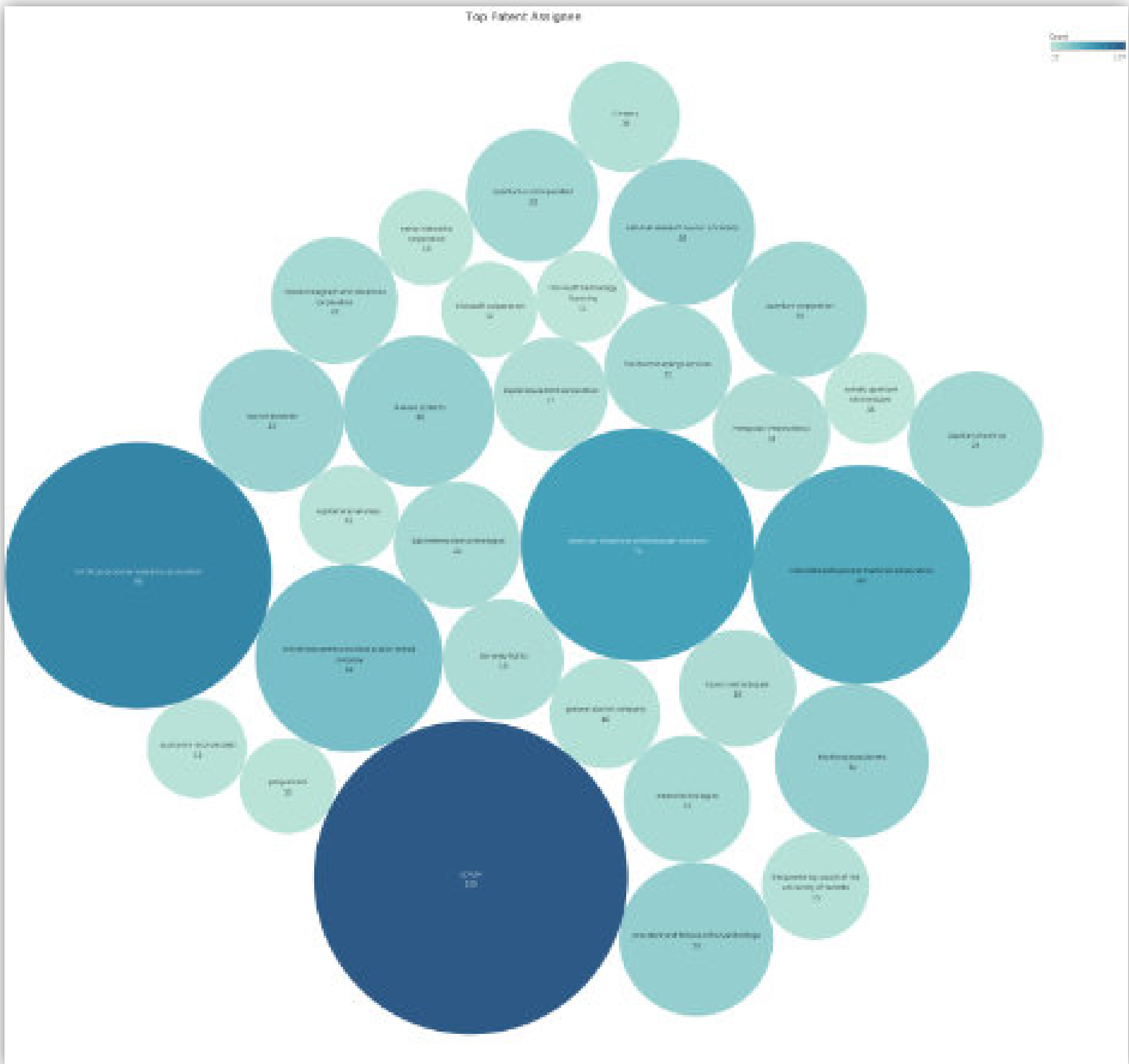


Figure 3. Top Quantum Patent Assignees for Filings in the Canadian Patent Office from 1970 to 2022.

Analyzing the Canadian Patent Office filings and granting through time, shown in Figure 4, it is possible to observe three different periods. The first, from 1974 to 1987, is the very early days of quantum technologies where all innovations were new and very little competition existed.

The second period covers 1988 to 2012, where it is possible to see a growth in velocity in the number of patent applications that slowly outpaces the number of patents granted, while some years have a burst of patents coming in that end up never being granted.

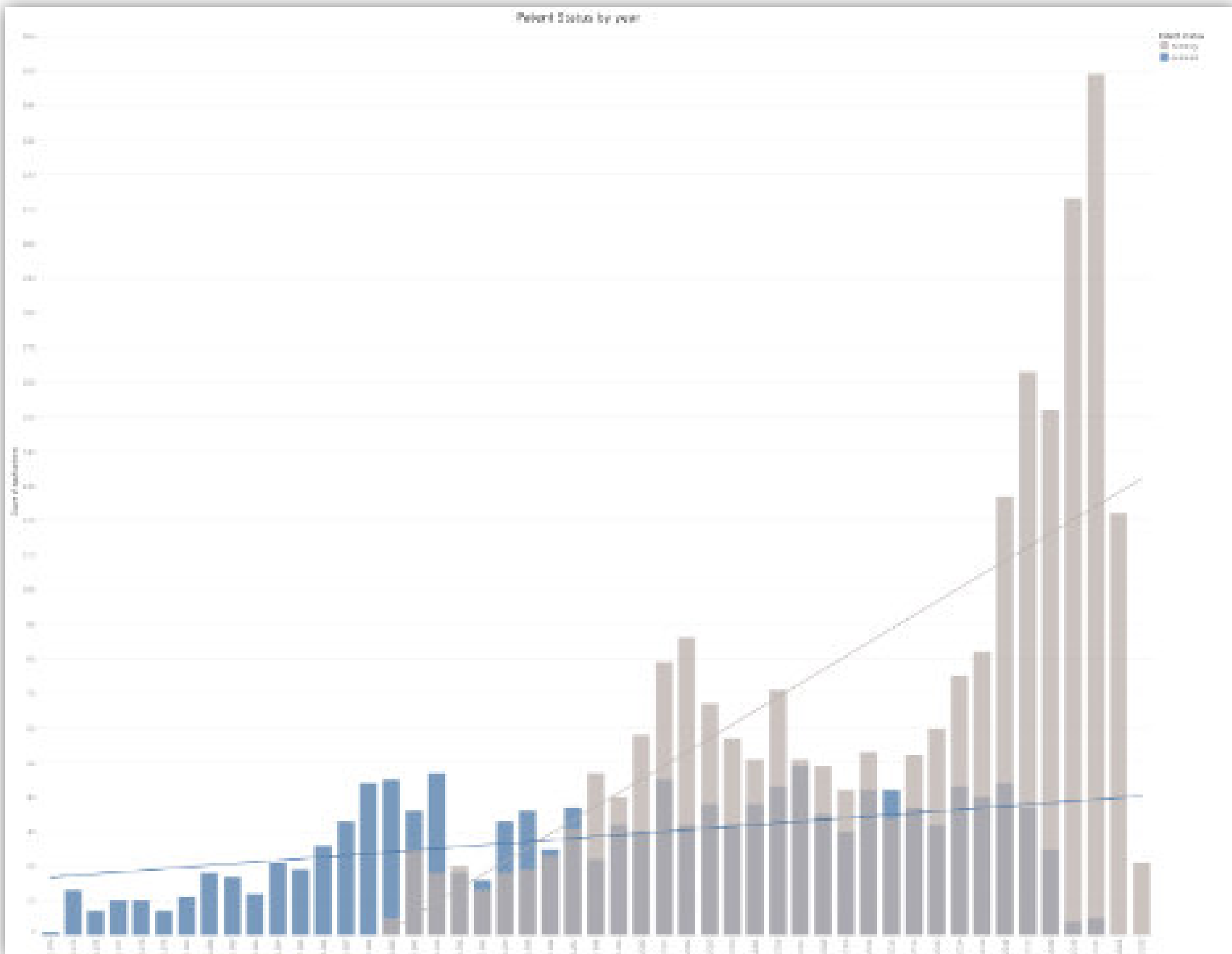


Figure 4. **Canadian Patent Office: Quantum Patent Applications and Patents Granted, 1974 to 2022**

In the third period, from 2012 to today, it is possible to see the ramping up of competition and of corporate actors trying to secure their part of the quantum market. Keeping in mind the 6-year wait time for the granting process to take place, the 2012 to 2018 period gives a good picture of the number of patent applications exploding and increasingly outpacing the number of patents granted. This can be explained by patent applications becoming more technically specific, and the expertise to understand and then grant the patents not always being available. It may also reflect some assignees applying for multiple, similar patents to maximize the likelihood of securing broad patent coverage as part of a competitive business strategy.

This last trend is indicative of a market becoming more mature and approaching the "market ready" stage of product development. It is impossible to know precisely where that point lies from patents alone, but corporate assignees do tend to apply for patents in areas they expect to be profitable.

arxiv – Innovation and Talent

Methodology and Caveats

The base quantum dataset from arXiv.org was created by bulk-downloading all papers in the quant-ph, cond-math, quant-gas, math.qa and gr-qc libraries in arXiv, keeping only papers from 2016 until the end of 2022, as well as pruning formats that couldn't be easily transformed to a text format, this left the data set with 77,372 papers.[23] From those papers, using a heuristic method chosen as a response to the amount of noise inherent to the source data, 4,129 affiliations were found as well as 69,342 separate authors. It is important to understand that the applied methodology, that has a strong capacity to capture repeating features (for example affiliations appearing in more than one paper), is less effective in capturing one–offs (meaning that organizational affiliations with one or two papers can fall through the net).

Once all papers had a set of associated authors and country affiliations, authors were matched to country affiliation based on statistical probability. This methodology covered most cases: most authors had clear country affiliations, confirmed more clearly with each year of data. An author having three potential Canadian affiliations and one potential American affiliation is matched with Canada. In aggregate, this leaves a less than 0.01 error rate based on a test set of 250 papers, but when the data is segmented to get a closer look, it is important to understand that it is impossible to forecast where those errors are, and, in consequence, it is impossible to determine the preciseness of small segment analysis, only the trends found in those analyses.

arXiv – Innovation and Talent: Data and Analysis

Authors, Affiliations and Publishing

Analysis of the arXiv dataset provides interesting insights into the global interest and participation in quantum physics research. It is notable that countries from all continents have contributed to the pursuit of quantum knowledge since 2016, albeit with varying degrees of involvement. This accessibility should be kept in mind for the rest of this report as it is the start of a funnel leading to the very small number of countries who are reaping the economic benefits of the start of the quantum revolution.

The leading contributors to quantum physics research, as indicated by the top 15 countries by author since 2016, have remained relatively unchanged, with the United States and China holding prominent positions. These two countries account for a significant proportion of the published articles, with China being the only country to experience growth in the number of authors during this period.

The United States has consistently been a prominent contributor to quantum physics research, with its leading research institutions and universities, playing a pivotal role in the field's growth and development. Conversely, China's rapid rise in the field can be attributed to their government's prioritisation of high technologies in their strategic planning which includes significant investments in quantum technologies, such as quantum computing, quantum communication, and quantum sensing. The Chinese government's substantial commitment to funding quantum research has led to the establishment of numerous research institutions and universities dedicated to the field.

While individually smaller, the top countries of the European Union come together to have an even greater impact than the United States or China. The existence of a European quantum strategy and historical collaborations between EU countries, puts the EU on equal measure with the US and China and, with the presence of CERN, arguably places the EU in the position of global leaders in terms of volume of quantum papers published.

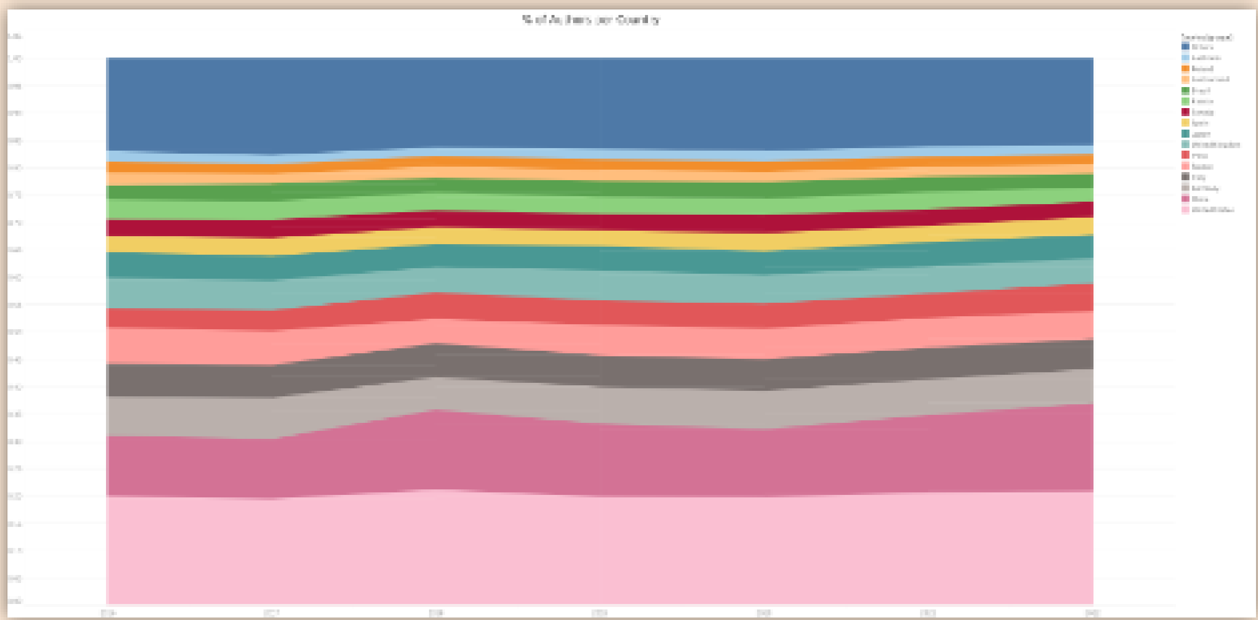


Figure 5. Percentage of Quantum Papers from the Top 15 Publishing Countries on arXiv.org by Country from 2016 to 2022

An important factor to consider when examining publications per country is the possibility of a paper being affiliated with multiple nations. For instance, publications emerging from CERN would be included in Switzerland's publication count, but they would also be attributed to any other country to which the authors have declared an affiliation. This can result in an inflation of the publication count for several other countries that have contributed to the paper, especially considering that such papers tend to have a higher number of co-authors than the average, sometimes reaching several hundred. For this reason, the couple of dozen papers with very high author counts (200+) were taken out of the data set.

This phenomenon of multiple affiliations can obscure the true research output of individual countries and complicate the evaluation of their contribution to the field. Nevertheless, it highlights the importance of international collaborations and the global nature of quantum physics research. It also indicates that cooperation between nations is critical for advancing research in this field, and that even smaller countries can play a significant role when they collaborate with other nations.

Attempts were made to normalize publication and author count per population, GDP, and other such metrics and led to unsatisfactory outcomes. Each approach tended to skew the results in a way to discount one country or another. The best example is by population, in which China and India disappear from the graph while Singapore comes out as a dominating force. This points to the need to develop a more nuanced normalizing tool, which could not be done in time for this report.

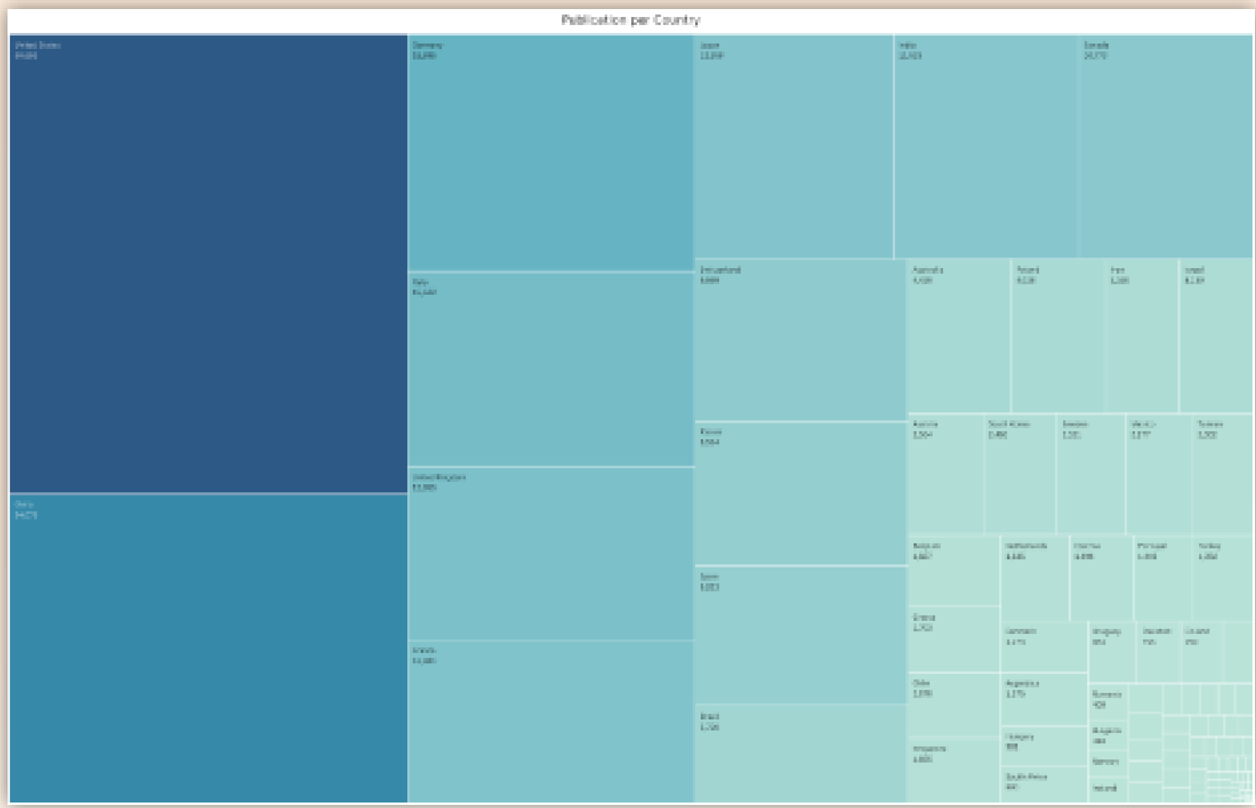


Figure 6. Number of Quantum Papers on arXiv.org by country from 2016 to 2022

A closer examination of the arXiv dataset pertaining to quantum physics research in Canada, shown in Figure 7, reveals several interesting insights into Canada's contributions to the field. Ontario is consistently the province with the most affiliated authors, with British Columbia and Quebec sharing similar numbers and Alberta also showing a significant number of authors. This implies that these provinces have been at the forefront of quantum physics research in Canada, with researchers and institutions based in all four provinces contributing significantly to the country's output in the field.

Focusing on specific institutions, the Perimeter Institute emerges as the most industrious contributor to quantum physics research in Canada, hosting the most authors each year and accounting for a substantial proportion of the overall Canadian author pool. The University of Toronto, McGill University, and the University of British Columbia are also notable institutions that have made significant contributions to the number of quantum physics papers produced in Canada, with each of them boasting relatively similar numbers of affiliated authors. The University of Waterloo – a smaller institution, but still with a larger than average cohort size – is also noteworthy, with its Quantum NanoCentre being a major contributor to the development of quantum publications in Canada.

The only province that does not show up in Canada's author count is Prince Edward Island, most probably due to the size of the province rather than anything else.

It is also interesting to note that, if the Perimeter Institute is taken out, the ratio of publications from each province then follows more or less the economic/population ratio of each province.

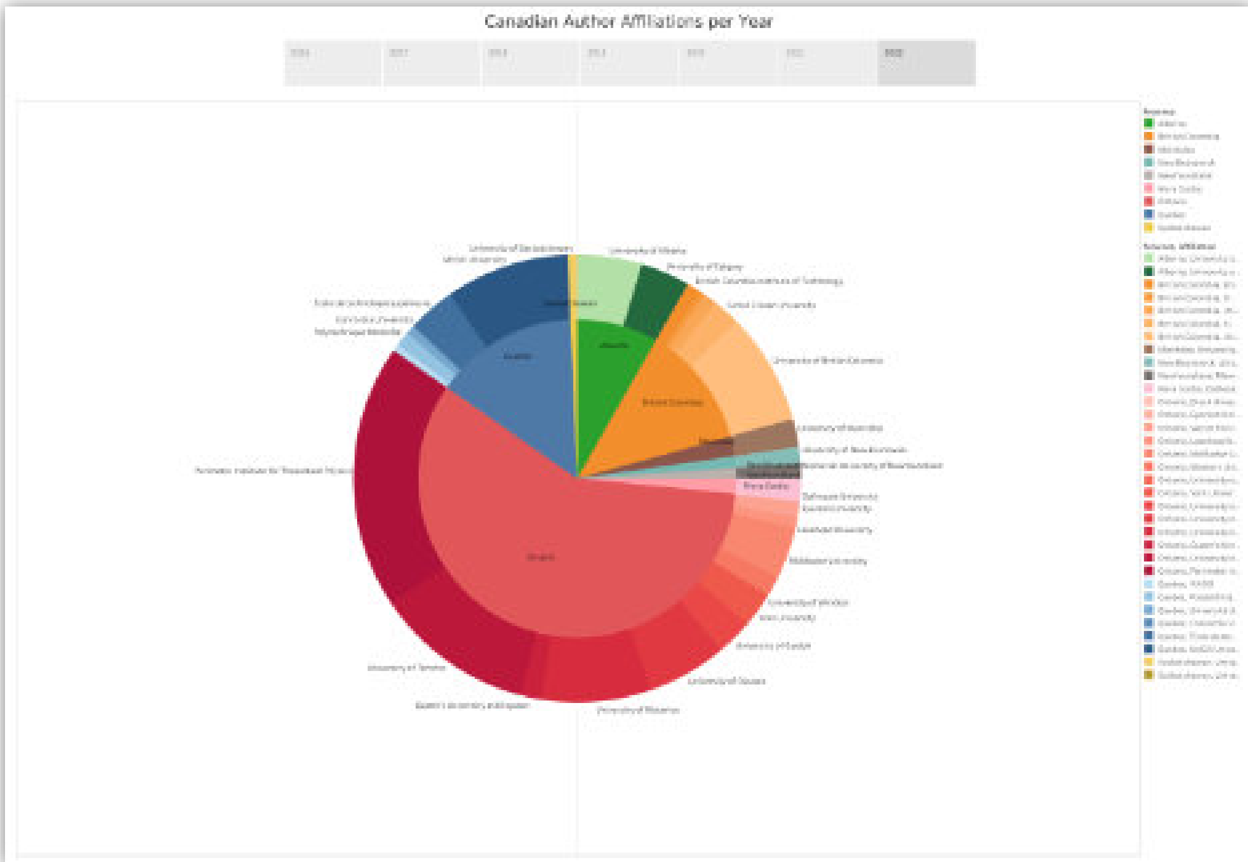


Figure 7. Number of arXiv Quantum Authors by Canadian Institution, 2016 – 2022

An attempt was made to identify the gender of quantum authors based on their names, to gain an insight into gender diversity in quantum research. However, the majority of quantum papers in the arXiv database give only initials for the first names of authors, so any estimate of the proportion of women or men in the sector cannot be found.

Collaboration and International Research

By mapping individual affiliations to countries, it is possible to identify how the world of quantum physics is built on international collaboration. Compared to most other academic subjects where collaborations tend to occur on a more local scale, it is notable that almost 90% of papers published on arXiv are international collaborations.

If those collaborations are mapped out, it is clear that they are not limited by political or economic boundaries. Contrary to other high-tech related fields where collaborations tend to flow between countries of the global north, with occasional touch points to countries like India or Brazil, the quantum physics field seems to have opened doors.[24]

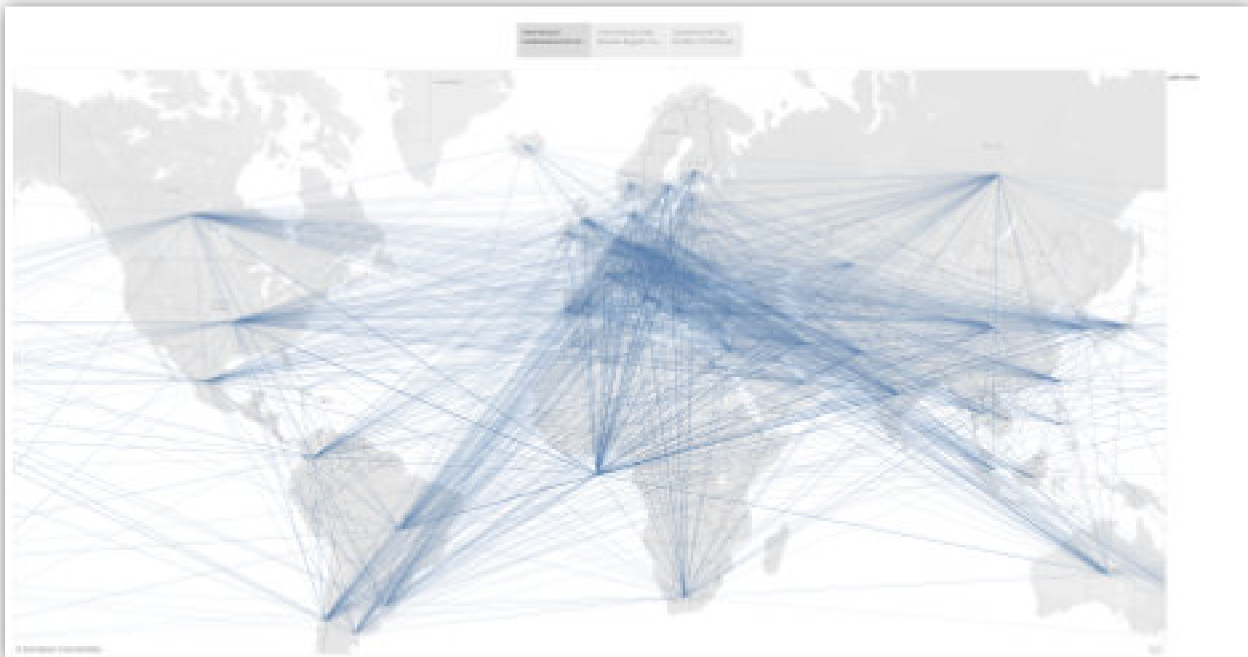


Figure 8. **Map of all International Collaborations on Quantum Publications from 2016 to 2022**

Drilling down into the collaboration networks in quantum physics research reveals two significant poles of research. Firstly, the United States stands out as a very open player with strong connections to Canada and European countries. The United States also has substantial research connections to India, Indonesia, and Australia.

Secondly, a European corridor from Germany to Italy passing through Switzerland seems to structure the European scene with strong links to the rest of Western Europe, North America, and China. The region's historical alliances, combined with the presence of research institutions such as CERN, make Europe a prominent player in the field of quantum physics research.

Notably, while China is a strong participant in quantum physics research, it appears to operate as a more closed ecosystem than other large countries. This may be due to political restrictions or other factors, but it is worth noting that this trend is also evident in other fields that have been tarjgeted as central to the Chinese government, such as artificial intelligence and computer science.[25]

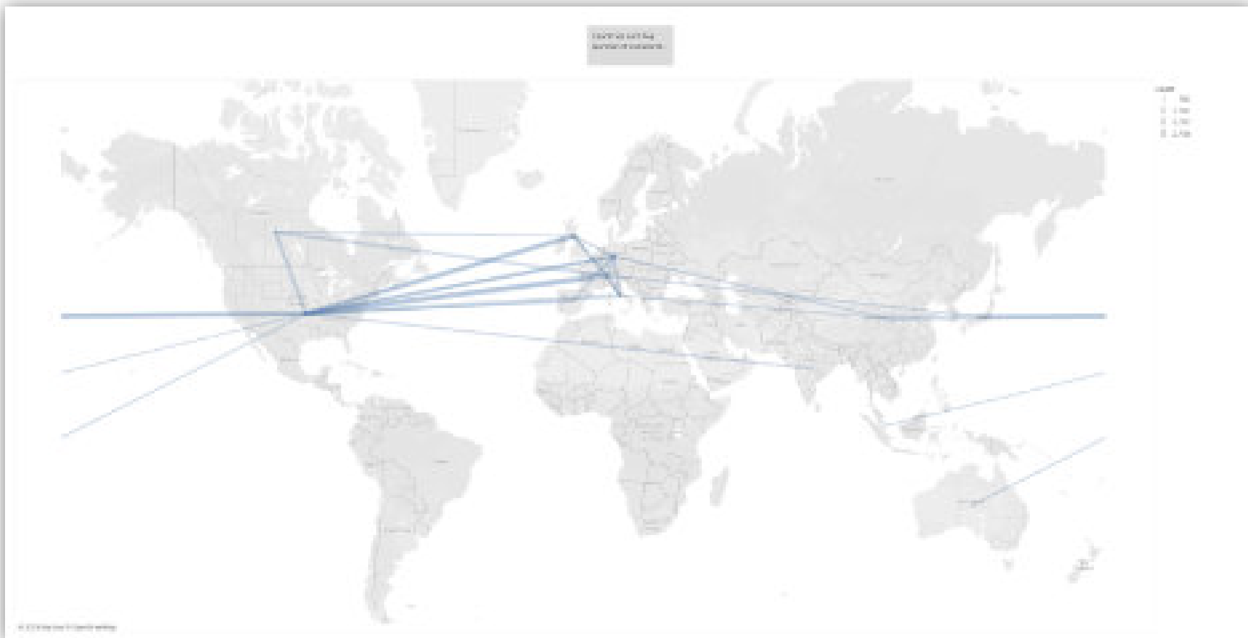


Figure 9. Map of International Collaborations of Top Countries on Quantum Publications from 2016 to 2022

Looking more closely into international collaborations with Canada (Figures 9 & 10), it is easy to see that they follow the same trend as the top players. The main pole of collaboration is with the United States with more than 1,800 papers created in US collaborations with Canadian authors since 2016. The second pole, the Germany–Switzerland–Italy corridor, has collectively seen more than 2,400 papers created, with 1,400 being with Switzerland alone. Other notable pairings are with the United Kingdom, China, and France with 885, 528 and 469 joint papers respectively.

From a more general perspective, it is also interesting to note that every country with authors publishing on arXiv has collaborated with a Canadian author at least once since 2016.

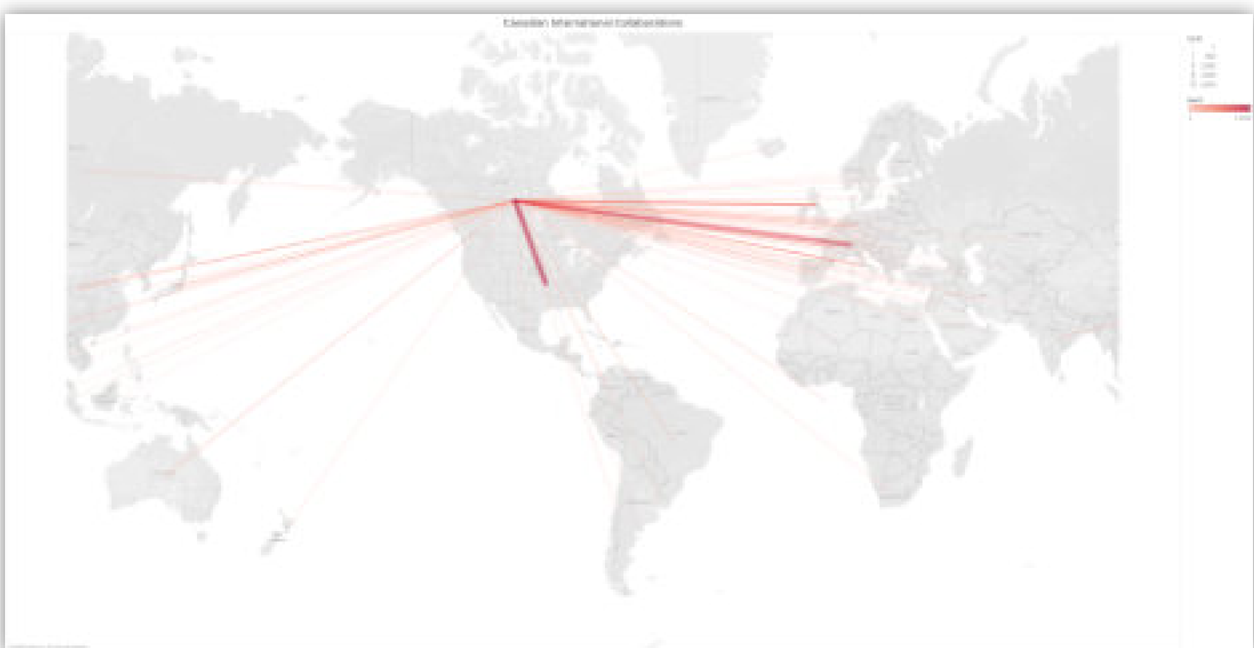


Figure 10. Map of Canada's International Collaborations on Quantum Publications, 2016 to 2022

Talent flow, attraction and retention

After country affiliations for each author are established, it becomes possible to track them from year to year, to understand the flow of research talent from country to country. Starting with changes between 2016 and 2017 and tracking changes in affiliation over five years to 2021–2022, it is possible to identify how many authors left and arrived in each country. This analysis supported the creation of an attraction and retention score for each country based on the overall number of authors moving into and out of each country that was then compared to the distance from the global average of authors leaving and entering countries.

The attraction/retention graph (Figure 11), shows that, year on year, the United States was the country that attracted the most authors as well as successfully retaining the most authors. This does not mean that the United States necessarily sees a corresponding growth in its overall quantum talent pool, as this only measures the flow of publishing authors. While the academic–to–industry pipeline is a well-documented phenomenon, it is important to keep in mind that many other strategies exist to grow the overall talent pools of countries.

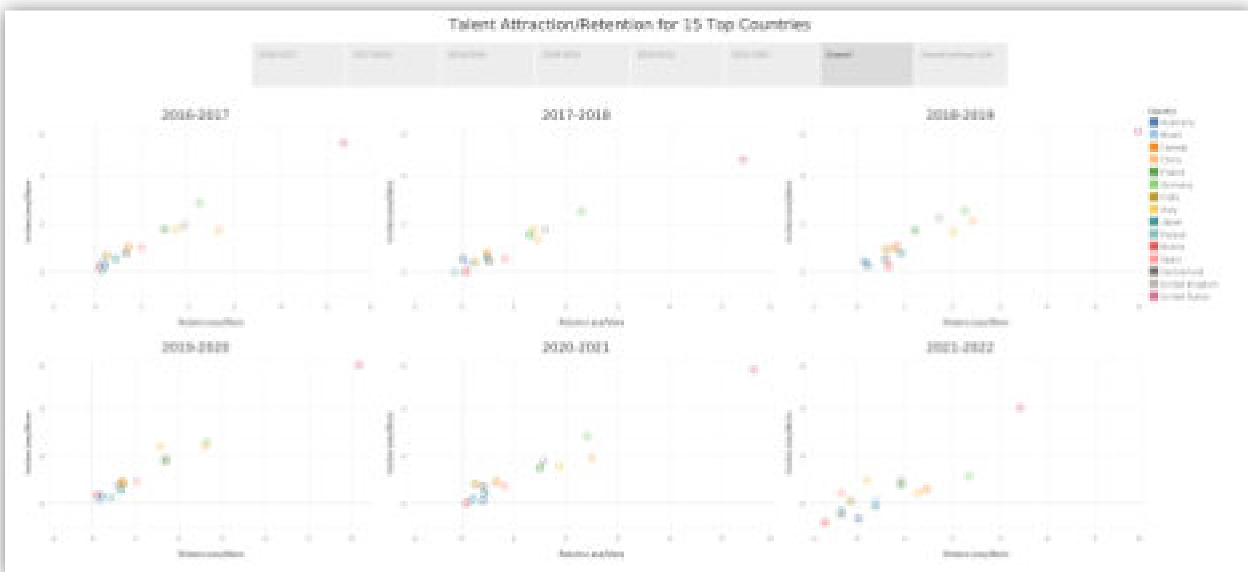


Figure 11. Talent Attraction and Retention for the 15 Most Active Countries, 2016–17 to 2021–22 (The Y–axis shows talent attraction and the X–axis shows talent retention)

Removing the United States as a relative outlier (Figure 12), it is possible to get a better understanding of how the other top countries position themselves. For most years, Germany seems to be able to attract more talent than all other countries, as well as performing well when it comes to retaining that talent. China also trends towards the head of the pack, having the best retention score for half of the years and being in the top in terms of attraction for most years.

Other European countries, France, Italy, and the United Kingdom, also lie toward the top of the list, often being in a cluster with China and behind Germany.

In contrast, Poland and Russia perform less well than their European counterparts, often dipping below the axis lines that join the space reserved for less 'attractive' countries.

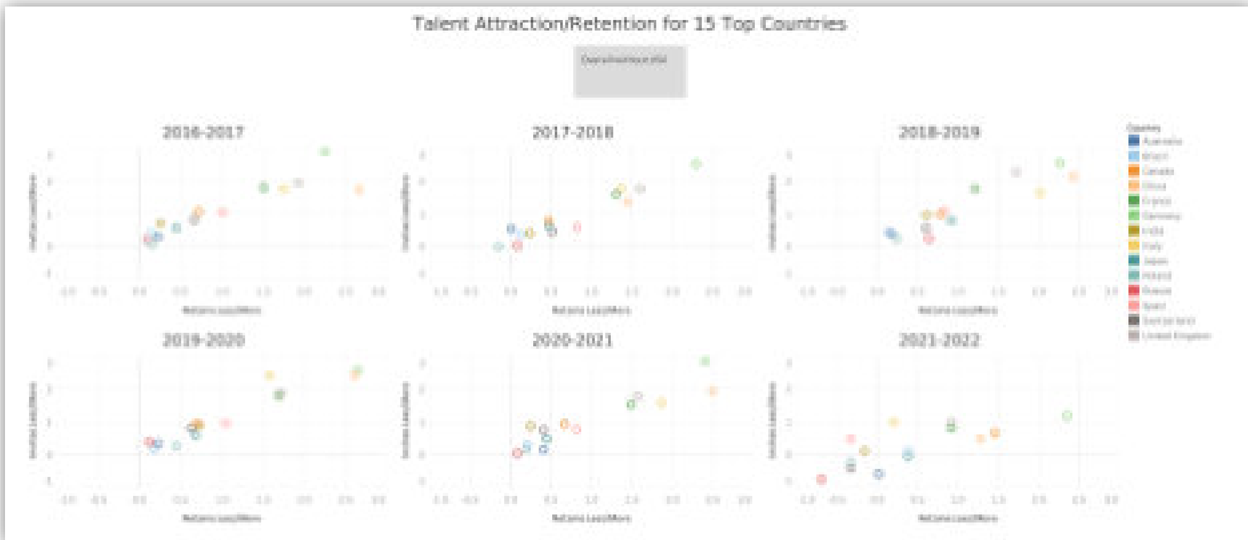


Figure 12. **Talent Attraction and Retention for the 15 Most Active Countries, Excluding the USA, 2016–17 to 2021–22 (The Y-axis shows talent attraction and the X-axis shows talent retention)**

Analysing the Canadian talent flow in more detail (Figure 13), it is possible to see an average outflow of talent mostly to the United States, China and to the European corridor.

The sharing of talent with the United States gives a good perspective on the overall trend that Canada is seeing. While many Americans come to study/work in Canada, the flow from the US to Canada being the biggest among all Canadian inflows, a greater number of Canadians move south into the US.

Without digging into the career path of each author moving from one country to the other, it is hard to give plausible reasons for the drain of Canadian talent, but certain trends do emerge; authors who move rarely come back and authors mostly move alone, which points to individuals relocating to advance their careers.

While looking at this data, it is important to keep in mind the limitations of the methodology used to collect the original data set. Since this is a small slice of the original arXiv dataset, the impact of potential errors in attribution can be important. It is important to understand that the trends shown in this graph have a high probability of being true, but the specific amounts are potentially off.

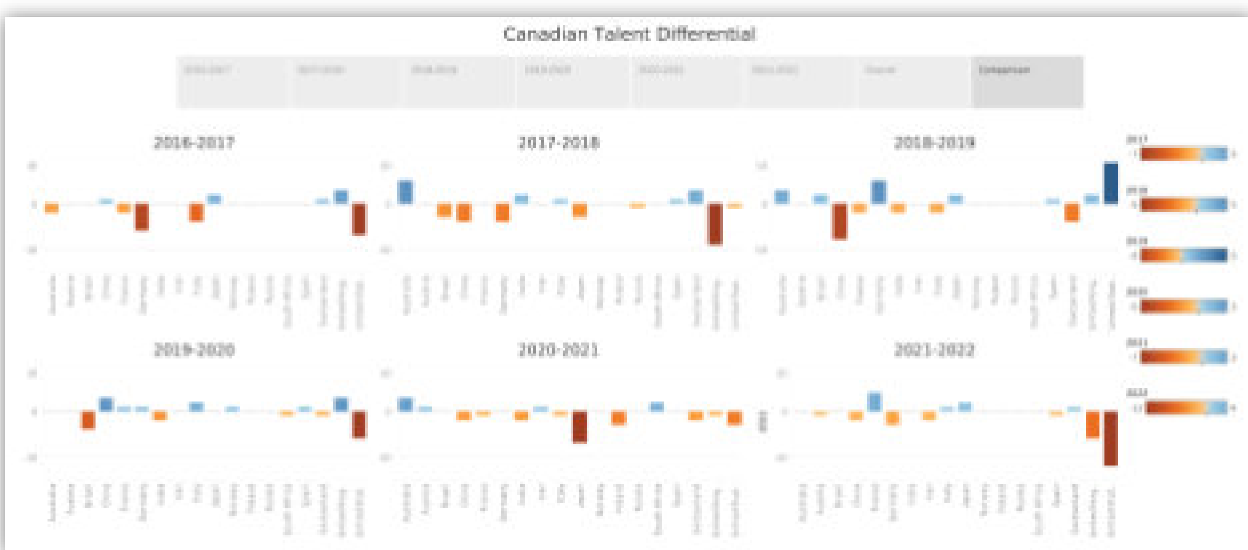


Figure 13. **Flow of Quantum Talent into and out of Canada, 2016 – 2022**

Social Media Self–Representation

Methodology and Caveats

As an emerging sector, the Quantum world has yet to define a clear and shared vocabulary for many subjects. In the case of talent, this means a lack of shared vocabulary to describe job titles as well as job responsibilities. This analysis started by searching for any profile based on the presence of keywords related to the field (e.g., "quantum computing", "quantum communication", etc.). These profiles were used to create a list of potential job titles and a list of negative keywords to remove (e.g., names of companies containing quantum but having nothing to do with quantum technology). Based on these lists self–reported data from social media was collected and aggregated to provide results based on the logic of the tech world's research–to–product pipeline. This aggregation cannot be perfect, as many of the job titles are open to individual interpretation (e.g., titles like quantum engineers were found to be a shorthand for both quantum software engineers and quantum materials engineers). It is important to note that social media self–representation is not a precise measure of worker numbers. As a result, it was chosen to use this data only to understand the overall trends rather than sharing precise, but potentially misleading, numbers.

Below are the different areas of work in the research-to-product pipeline:

Subject Experts

Research

The first stage of the pipeline groups together fundamental and applied researchers both from universities and R&D departments of companies. This stage is populated mostly by PhD holders and students working in academic labs as well as in companies with internal labs.

Software

The second stage: in parallel with hardware, the software stage groups software engineers and developers, cyber security experts, data scientists, machine learning engineers, etc. Most workers in the software stage work outside academia in startup companies and in large, established companies that are working to create the first market–ready quantum software.

Hardware

The second stage: in parallel with software, the hardware stage groups hardware engineers, materials engineers, microelectronic engineers, most technical experts and quantum engineers, as well as photonic engineers. The majority of hardware employees work in the private sector in established companies, with a small minority working in academic environments as lab technicians.

Product to Market

Productization

The last step, productization, groups everyone needed to take hardware or software and make it into a product on the market. This stage brings together designers, market analysts, sales and marketing experts, product managers, project managers, etc. It is important to note that this step was the most complex when identifying individuals with the skills to work in the quantum sector (e.g., a person with an academic background in quantum physics but working as a product manager) from those actually working for companies in the quantum field. This nuance puts the product-to-market workers in a different category from the subject experts, as it is easier to be confident that a "quantum engineer" works in the quantum industry than it is to be confident that a "marketing expert" with mentions of quantum in his or her profile actually has the skill set to work in the quantum sector.

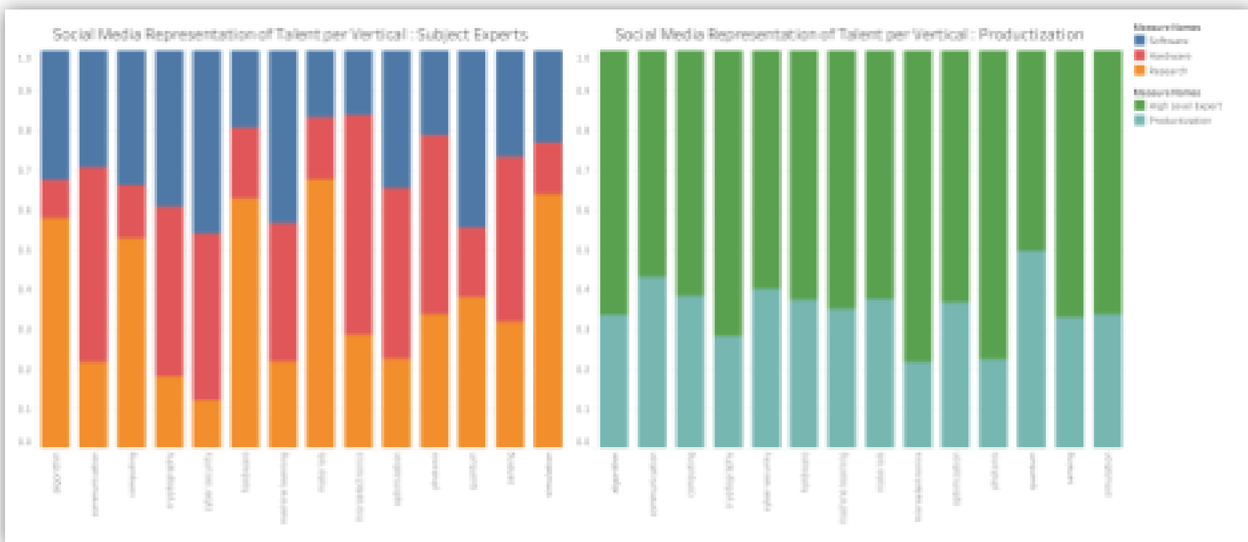


Figure 14. Percentage of Research–to–Product Talent Pipeline Stages for 14 Quantum Verticals. Grouping based on titles and description.

Social Media Self–Representation: Data and Analysis

On the global scale, social media self-reported data shows the quantum world is moving towards commercialization but has many sub-verticals which are still deeply rooted in the research world. Looking at the graph above (Figure 14), the research, hardware and software professionals are organized to show their respective percentage of the overall quantum experts self–reporting as working in the quantum industry; while the productization workers are presented as an estimated percentage compared to the other three combined.

For verticals more rooted in the research world – the algorithms, computing, materials, modalities, and simulation sectors – more than half of their workers are researchers. While having a high proportion of researchers can be a relatively normal state for some verticals such as quantum materials, which is, by its nature, an R&D field even in the commercial sector, generally, a high proportion of researchers in a vertical indicates that vertical is still maturing and not yet ready to bring products to market.

By contrast, verticals such as communication, cryptography, cyber security, machine learning, microelectronics and optimization, have less than 20% of qualified workers self–represented as professional researchers. Generally, these verticals are closer to being market mature. Microelectronics is a good example with many profitable companies already operating in the microelectronics vertical. Similarly, the quantum vertical for cyber security is part of an established business where research is part of companies' day-to-day commercial work.

When looking at the productization part of the graph, it must be noted that the general quantum vertical shows that a large proportion of workers self-represent as having some knowledge of quantum physics, mostly through an academic qualification in physics. In the above graph, the productization section shows there is potentially one productization worker for every two subject experts. The verticals with the largest proportion of productization workers are generally the most commercially mature. This suggests three possible conclusions: the maturity of those fields could create a self-selecting pressure, pushing out workers whose high level of technical expertise is no longer required as the field becomes mor commercially oriented; some fields could be more specialized than others, requiring high levels of technical input on an ongoing basis; or as some verticals tend to be hardware-intensive, differing levels of technical experts employed in a field might simply be a feature of hardware vs software verticals. As the data used to create the graph is based on social media self-representation it is hard to know with precision what factors are at play; more in–depth research is needed.

No data on the gender of participants in the quantum field can be gleaned from social media self-reported data without contravening the privacy and data access rules of the platforms providing the data.

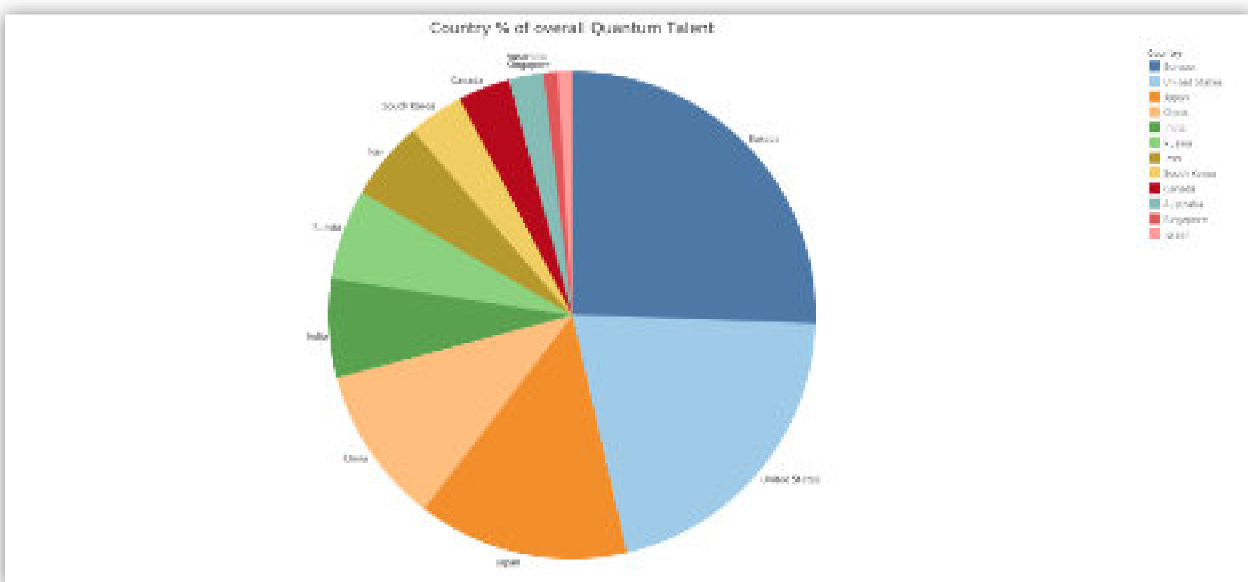


Figure 15. Percentage of Overall Quantum Talent by Country

Figure 15 shows the social representation data by country, adjusted for adoption rate per country. The countries with the highest proportion of self-reported quantum experts are the United States, Japan, and China. Europe, North America, and East Asia all have about the same number of workers. Per capita, Singapore has the most quantum workers by a very large margin.

Conclusion

In the 25 years since the demonstration of the world's first two-qubit supercomputer in 1998, interest and investment in quantum technologies and quantum computing have grown significantly. Early government funding for quantum research has created a foundation of quantum talent, expertise and technology that underpins the development of today's business sector for quantum.

Analysis of government data, university programs, venture capital investments and early use-cases for NISQ quantum computers describe the macro-environment for the operation of today's quantum computing companies. We know that the number of quantum computing companies in the world has grown from 42 in 2015 to 195 in 2021[26], that international investment in commercial development of quantum computing has accelerated rapidly, with $1.3 billion being invested in quantum startups in the 3 years from 2018 to 2021[27] and that the explosion of business activity in quantum computing companies is happening in spite of a chronic talent shortage[28].

This analysis of the quantum technology and computing ecosystem in Canada focuses on the micro-level, examining online datasets to identify trends and themes in quantum talent and innovation, capturing changes in this fast-changing sector.

Quantum technologies are moving from research labs and universities to corporate and commercial environments so rapidly that the transition will not be captured by many government and industry monitoring systems such as employment statistics.

Analysis of online information on patent filings, arXiv publications and self-reported expertise and employment status in social media, provide a window onto today's quantum sector and support the key findings of this report.

Innovation in Quantum

Academic research

Analysis of the arXiv.org dataset shows global interest in quantum physics research with contributions from countries on all continents since 2016.

Global Collaboration

International collaboration is a key feature of quantum physics research, with almost 90% of papers being collaborations.

Patents

The accelerating rate of filings for quantum patents reflects both the transition of innovations out of research labs and into companies and an increase in competition between quantum companies.

The Global Competition for Quantum Talent

Quantum Talent

Based on self–reported data, it is possible to see that most quantum–related fields are still firmly rooted in the world of academic research. Some verticals are showing signs of maturing into market–ready fields, with a growing percentage of workers moving to commercial software or hardware roles.

Talent Flow

Canada is among the leading countries when it comes to attracting and retaining expert quantum talent. However, Canada still has a negative net outflow of talent to the United States and some other larger ecosystems such as Europe and China.

Postscript

This analysis of the Canadian quantum ecosystem is a first step in tracking and understanding the emergence of commercial quantum computing as this disruptive technology emerges for application to real-world business and social challenges.

The Quantum Algorithms Institute is interested in creating an accurate picture of Canada's quantum ecosystem as it develops. Any reader is welcome to share questions, comments or omissions.

Data Analyst and Authors

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Louise Turner

Footnotes

[1] "State of Quantum Computing: Building a Quantum Economy." Insight Report, World Economic Forum, September 2022, p. 12.

[2] arXiv.org is a popular online repository for electronic preprints of scientific papers in the fields of mathematics, physics, astronomy, computer science, quantitative biology, and more. All papers on arXiv are freely accessible to anyone with an internet connection.

[3] "State of Quantum Computing: Building a Quantum Economy." Insight Report, World Economic Forum, September 2022, p. 4.

[4] Bobier, Jean-Francois, Antoine Gourevitch, Edward Tao, and Matt Langione. "What Happens When 'If' Turns to 'When' in Quantum Computing" Boston Consulting Group, July 2021, p. 2.

[5] Smith, Collin, et al. "Current and Future Role of Haber–Bosch Ammonia in a Carbon-Free Energy Landscape", Energy & Environmental Science, vol. 13, no. 2, December 28, 2019. Cited in "How Can Your Quantum Vision be Transformed into a Sustainable Reality", EY UK, July 8, 2022.

[6] Bobier, Jean-Francois, Antoine Gourevitch, Edward Tao, and Matt Langione.What Happens When 'If" Turns to 'When' in Quantum Computing, Boston Consulting Group, July 2021, p. 2.

[7] Clinton-Tarestad, Piers, and Harvey Lewis. "Preparing for the Quantum Computing Future", EY Quantum Readiness Survey 2022. EY, June 27, 2022, p. 15.

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[9] Press, Gil. "27 Milestones in the History of Quantum Computing." Forbes Magazine, May 18, 2021.

[10] Ibid.

[11] "The Quantum Decade: A Playbook for Achieving Awareness, Readiness, and Advantage." IBM Institute for Business Value, June 14, 2021, p. 11-12.

[12] Bobier, Jean-Francois, Antoine Gourevitch, Edward Tao, and Matt Langione. "What Happens When 'If' Turns to 'When' in Quantum Computing." Boston Consulting Group, July 2021, p. 1.

[13] "Transitioning to a Quantum-Secure Economy [White Paper]." World Economic Forum, September 2022, p. 5.

[14] "State of Quantum Computing: Building a Quantum Economy." Insight Report, World Economic Forum. September 2022, p. 10-11.

[15] Bobier, Jean-Francois, Antoine Gourevitch, Edward Tao, and Matt Langione."What Happens When 'If' Turns to 'When' in Quantum Computing." Boston Consulting Group, July 2021, p. 1.

[16] State of Quantum Computing: Building a Quantum Economy. World Economic Forum Insight Report, September 2022

[17] What Happens When 'If" Turns to 'When' in Quantum Computing, Boston Consulting Group, July 2021

[18] Quantum computing funding remains strong, but talent gap raises concern, McKinsey Quantum Technology Monitor, June 2022

[19] EY Quantum Readiness Survey 2022, June 2022

[20] Valigra, Lori. "Canada Lays the Groundwork to Become a Powerhouse in Quantum Technology." Science | Business, June 23, 2022

[21] "Driving Canada's Industrial and Academic Eminence Towards a National Quantum Strategy." IBM, May 2021.

[22] Press, Gil. "27 Milestones in the History of Quantum Computing." Forbes Magazine, May 18, 2021.

[23] While some efforts were made to filter out false positives, such as economic papers talking about quantum growth of markets, efforts to segment papers based on subjects proved to surpass the scope of this report. Further collaborations with subject experts will be needed to cluster keywords in a way to parse through what is otherwise a very noisy data set.

[24] Thelwall, Mike & Maflahi, Nabeil "Academic Collaboration Rates and Citation Associations Vary Substantially Between Countries and Fields."

[25] Gagne, JF. "Global AI Talent Report 2020."

[26] State of Quantum Computing: Building a Quantum Economy. World Economic Forum Insight Report, September 2022, Page 12

[27] What Happens When 'If" Turns to 'When' in Quantum Computing, Boston Consulting Group, July 2021. Page 1

[28] Quantum computing funding remains strong, but talent gap raises concern, McKinsey Quantum Technology Monitor, June 2022, Page 8