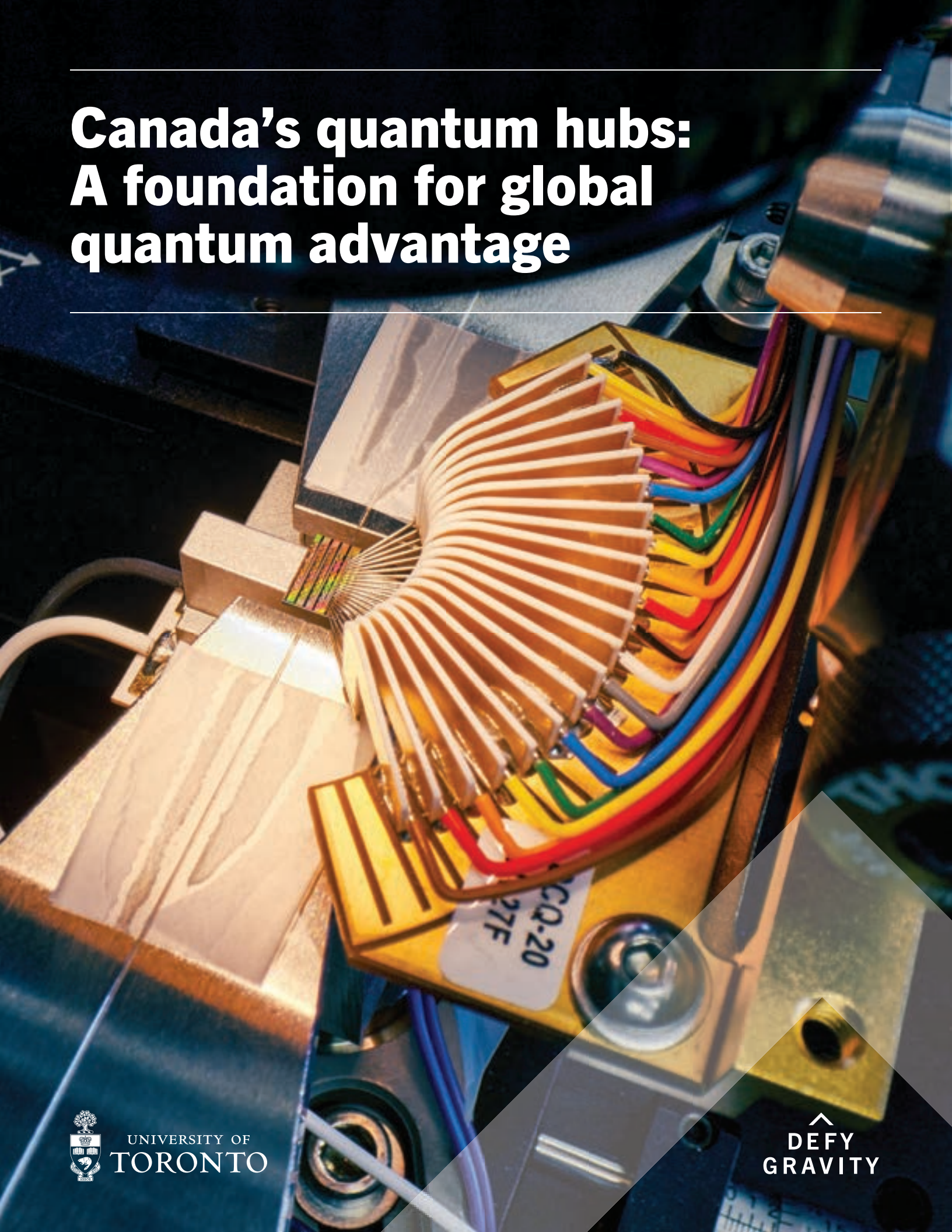
Canada's quantum hubs: A foundation for global quantum advantage



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The quantum opportunity

Canada can leverage the strengths of quantum hubs across the country to compete in the growing global race to develop quantum technologies and applications, a new report argues.

These hubs have grown with support from public investments and are now home to globally ranked quantum-based companies, high-tech talent, and the university research that is critical to this emerging sector. Several strong quantum clusters — Toronto-Waterloo Innovation Corridor, Sherbrooke-Montreal, Calgary, and the Vancouver area — are identified in the report as the foundation for future growth.

With the largest number of quantum companies, a healthy and distinct research commercialization pipeline, and a large tech and quantum-ready workforce, the Greater Toronto Area (GTA) is Canada's most significant quantum cluster. The University of Toronto and the Creative Destruction Lab at U of T's Rotman School of Management — the country's only entrepreneurship program dedicated to quantum-based startups — are pillars of the GTA cluster, the report states.

Commissioned by the U of T and conducted by Deloitte, the report's aim is to inform the development and implementation of the National Quantum Strategy announced in January 2023.

As with artificial intelligence, a field that was advanced through the Pan-Canadian Artificial Intelligence Strategy, quantum technology is a significant economic opportunity. Research commissioned by the federal government has projected a $139-billion market and more than 200,000 jobs created by 2045.

Quantum technologies are gaining increased attention as the federal government and provincial counterparts work to modernize Canada's economic sectors. Quantum applications have the potential to support and increase security for the financial, telecommunications, and transportation and logistics sectors, among others, while driving advances in artificial intelligence applications.

At the same time, the report cautions that other countries' national quantum strategies will draw the world's best talent and capital. To compete, Canada's national quantum strategy must recognize the stakes of the quantum race and prepare to support this transformative field.

A global race in a strategic sector

Among the first countries in the world to develop a national artificial intelligence strategy and implement parallel public investments, Canada was also a pioneer in its support of quantum research.

Investments in three quantum research institutes and a government research initiative opened research and commercialization avenues, continues to train new talent, and helped fuel quantum-based companies that have drawn significant venture capital. Examples include Xanadu, now a Canadian unicorn, D-Wave and Zapata, as well as hundreds of quantum-focused startups in Ontario, Quebec, and British Columbia. As the technology matures, these firms are all poised to benefit and grow.

Most recently, the federal government announced a national quantum strategy that will inject $360-million over seven years to the pillars of research, talent and commercialization. Canada's efforts parallel those in other countries: According to a 2021 CIFAR report, 17 countries have strategies to support research and development in quantum technologies while another 14 countries are participating in European initiatives.

A strong economic case exists for supporting quantum R&D:

- Increased security for financial and defence sectors through telecommunications and cybersecurity applications.
- Optimization of logistics and operations in the financial, manufacturing, and transportation industries.
- New materials discovery through simulations enabled by quantum computing that can process information at much greater speed than conventional computers.
- Enabling new capabilities in the artificial intelligence sector. Indeed, a U.S. report underlined that "AI sits at the center of the constellation of emerging technologies," with quantum science both driving and being supported by AI.

Deloitte's survey of other countries' quantum investments and outputs reveals that national investments to date are moderate in comparison to those of allies and competitors. If Canada aims to be at the forefront of quantum research and its applications, investments and support for the ecosystem must be reinforced.

Bench-marking international investments

Deloitte's analysis underlines that few countries will be able to compete with the top global leaders and particularly with China, as the chart below shows. In this comparison, current levels of federal investment are at risk of falling behind as other countries bolster their support. At the same time, when Canada is compared to countries with similar research profiles (as measured by the number of annual publications and their impact), it ranks among the top producers of knowledge in the quantum field.

The Global Race for Quantum Science

Total National Investment by Country	Recent Components	Investment Components	Key Area of Investment Focus
China $25.3 billion	**$15.3 Billion**	Includes investments through the most recent five-year plan for the technology, and support from 2011–2018.	Quantum Communications
Germany $4.8 billion	**$2.4 Billion**	Support announced in Budget 2021, adding to $2B included in 2018: From Basic Research to Market strategy.	Quantum Computing
United States $2.8 billion	**$500 million**	Allocated in the CHIPS and Science Act toward quantum network infrastructure, adding to support through the National Quantum Initiative Act.	Quantum Information Science
Canada $1 billion	**$360 million (Cad.)**	National Quantum Strategy funds allocated over next 7 years, building on support in last decade.	Quantum research and commercialization

Data sources: *World Economic Forum. State of Quantum Computing: Building a Quantum Economy; National Quantum Initiative. quantum.gov; Federal Ministry of Education and Research, Germany. Quantum technologies, From Basic Research to Market; Innovation, Science and Economic Development Canada. National Quantum Strategy Consultations: What We Heard Report. All figures USD except where indicated.*

Indeed, as countries define appropriate levels of investment in quantum technologies, several are increasing public support. Along with China, India, Germany, and France are significantly building their quantum capabilities. And with the CHIPS and Science Act, the United States has indicated it is also seeking to develop key technologies, translate advanced research, and grow the STEM workforce. While not the key aim of the Act, quantum-specific measures will deliver infrastructure to researchers and industry and educate a quantum-ready workforce, recommitting the United States to the National Quantum Initiative it released in 2018.

As the technology develops, Canada's calibration of its investments against global peers will make a material difference to the ability of our firms and researchers to succeed.

Comparative quantum investments by countries leading in quantum research output

Country	National GDP ($U.S. dollars, trillions)	Public quantum investment ($U.S. dollars, billions)	Spending as % of GDP
China	$18.3	$25.3	0.13
Germany	$4.0	$4.8	0.12
France	$2.8	$2.2	0.08
Canada	$2.2	$1.0	0.05
U.K.	$3.2	$1.2	0.04
Russia	$2.1	$0.7	0.03
India	$3.5	$1.0	0.03
United States	$25.0	$2.8	0.01
Japan	$4.3	$0.7	0.02

Data sources: *IMF: World Economic Outlook Database; U.S. investments in the National Quantum Initiative identified above will be enhanced through the $550 billion in support for advanced sectors contained in the CHIPS and Science and Inflation Reduction Acts.*

Canada's research advantage

Several quantum hubs across the country are critical to Canada's performance in this global race.

The analysis by Deloitte found these clusters demonstrate the following attributes:

- Presence of a range of post-secondary educational institutions and academic research institutions.
- Relatively high concentration of a highly educated population.
- Presence of large and influential companies across several fields.
- Ability to attract and retain international investment and talent.
- Access to capital.
- Networked or linked transit systems and infrastructure.
- Presence of industry associations, community groups and forums for industry to convene.

Deloitte's analysis suggests that the University of Toronto's assets in each of these areas, particularly its research strength and unparalleled commercialization pathways, are supporting the GTA's ranking as the country's strongest, home-grown private sector in quantum technologies.

The Quantum Opportunity: Sector Applications
Quantum technologies will increase productivity in many current industry sectors

Financial Services

Quantum computing promises better algorithms optimizing everything from financial modelling to trading strategies and asset valuations, delivering better results to investors.

Natural Resources

Quantum sensing promises more accurate monitoring of oil and gas reserves, mineral deposits, as well as better management of energy resources.

Health and Life Sciences

Quantum imaging promises more accurate scans of the human body, and quantum computing may accelerate novel drug development capabilities.

Technology, Media and Communication

Quantum communication and crytopgraphy promises more secure, less energy intensive communications, new semiconductor materials and network optimization, enabling better communication.

Specifically, the GTA's capabilities include:

- The Creative Destruction Lab (CDL), Canada's only quantum-focused entrepreneurship program.
- An estimated 22 quantum companies — the highest number in the country for one region.
- $5.5 billion in venture capital for tech, almost five times the amount of venture capital in the Greater Vancouver Area.
- U of T's Center for Quantum Information and Quantum Control, an interdisciplinary research center.
- Globally-leading AI talent at the Vector Institute, many of whom serve as U of T faculty and are advancing quantum science and technology through innovative research-based startups and ground-breaking research.
- The most tech workers of any Canadian region, with 250,000 technology-focused workers and 25,000 STEM students graduating each year.
- The GTA is ranked 3rd in CBRE's Scoring Tech Talent report in 2022 and trails only the San Francisco Bay Area and Seattle.

The Creative Destruction Lab's Quantum Stream — the country's only dedicated quantum, early-stage incubator — is a critical element in the GTA quantum ecosystem.

For the past 5 years, the program has brought together entrepreneurs, scientists, investors, and technology partners to build ventures in this emerging domain. This unparalleled program provides entrepreneurs with the mentorship, quantum systems (via Xanadu, Zapata Computing, D-Wave Systems, IBM Q and Rigetti Computing), technical validation and capital needed to succeed.

CREATIVE DESTRUCTION LAB

The CDL:

Has supported
120+
early-stage quantum startups from
35+
countries that have collectively raised
$300+ million

Operates
20
startup streams

Realizing the potential of quantum technologies through research

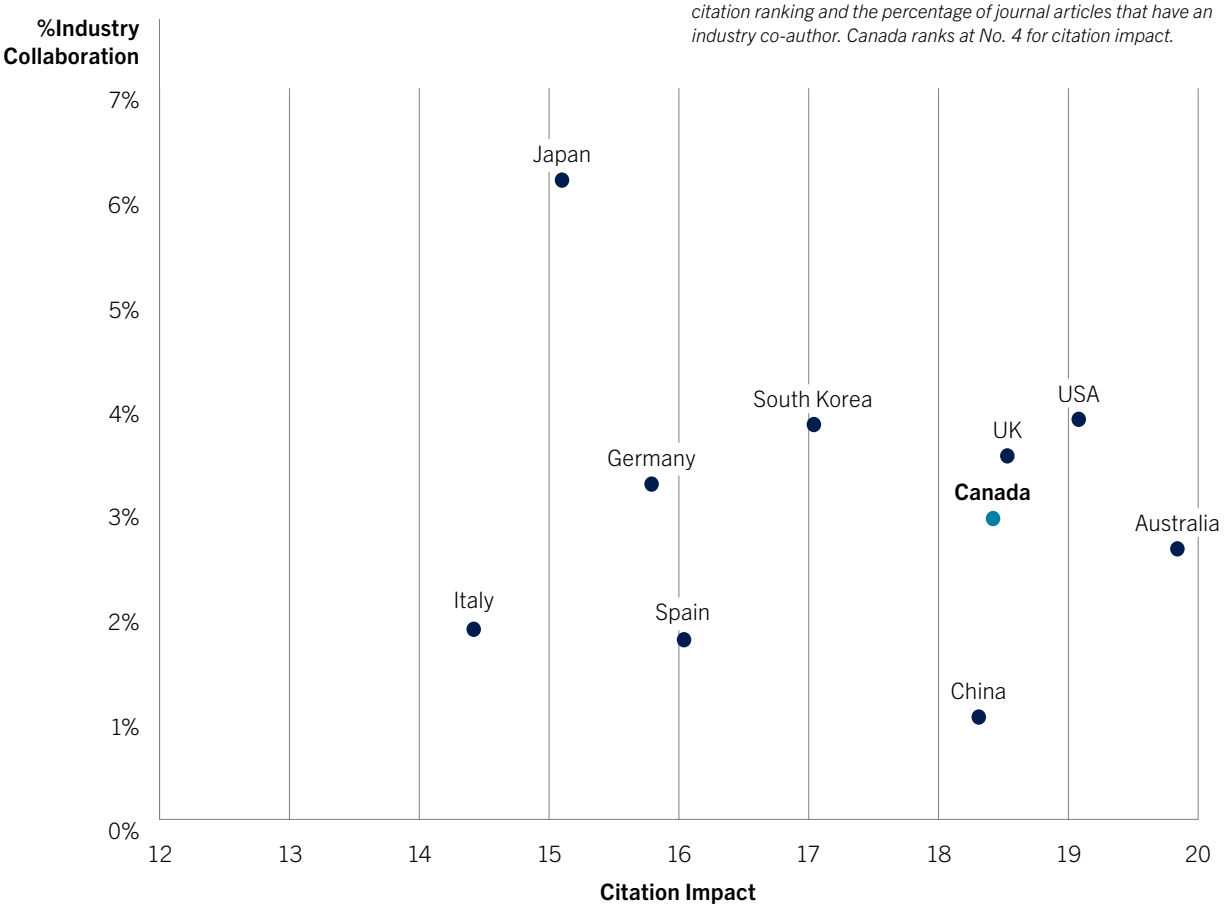
The National Quantum Strategy recognizes that supporting Canada's "research base is essential to ensure leadership in quantum science and technology." And in a recent report, the World Economic Forum stated that it is not yet clear which research path will lead to quantum advantage in computing. Therefore, multiple paths must be pursued.

Deloitte's report provides insights into how Canada's progress in quantum compares to that of other jurisdictions.

- Canada currently ranks at No. 4 in the world in the significance of its research (as measured by the citation impact of publications.)
- Japan, the U.S. and South Korea lead in the percentage of publications that feature collaboration with industry.
- Among the top five countries in volume of research, China is leading in the number of quantum papers, overtaking the United States in 2015.
- Notably, China's and India's volume of publications has accelerated much faster than other countries'.

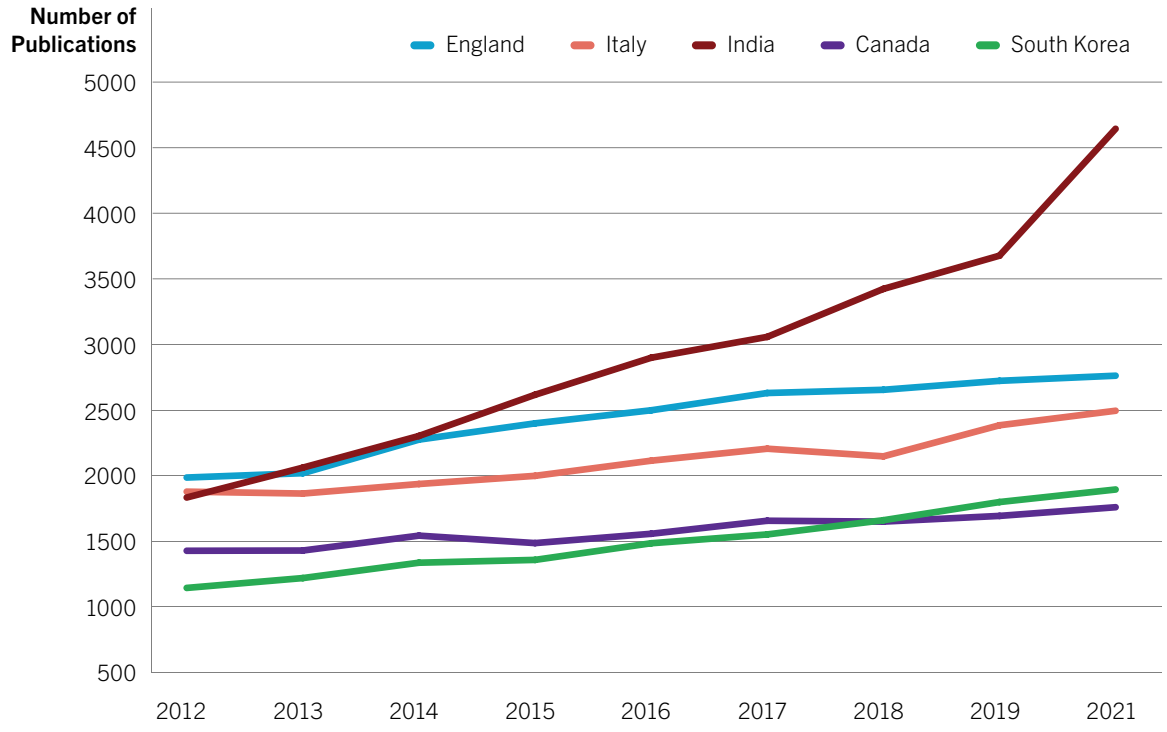
Quantum research impact by country: 2017–2021

Data sources: *The research impact of countries that are leading in the quantum research field is illustrated through two metrics: national citation ranking and the percentage of journal articles that have an industry co-author. Canada ranks at No. 4 for citation impact.*



Photo, left: U of T Engineering PhD candidate Jehad Abed with a vial of a catalyst for hydrogen production, discovered through a quantum-inspired computing technique developed with Fujitsu Research.

Number of quantum publications: Canada and comparable countries, 2012–2021



Data sources: *Scientific American. 2022. "China is Pulling Ahead in Global Quantum Race, New Studies Suggest"; European Commission. 2022. Quantum Technologies Flagship; Data sourced by the University of Toronto from Clarivate Web of Science.*

By volume, Canada's leading universities and science institutes are producing quantum research that place Canada in the No. 12 spot globally in this group, with a total of 8,570 papers since 2017.

As the analysis of research publications from comparable countries shows (above), Canada's increase in research production has been steady, slower than that of comparable countries. India, for example, increased the rate of growth in publications by double digits most years between the period of 2012–2021. Canada's total percentage increase in the same period was ~15 per cent, with the period of 2020–21 registering a 1 per cent decline.

Ensuring investments are targeted to ecosystems with the necessary research and physical infrastructure to attract the world's top quantum researchers will be increasingly important.

The University of Toronto: a global powerhouse in quantum research

The impact of U of T's quantum research place it in the No. 5 spot among universities that are leading producers of quantum research. Over the period 1980 to 2022, the University of Toronto has contributed the highest number of publications to the national total.

U of T's status as a national powerhouse of quantum research is based on several attributes of its quantum and research ecosystems:

Researchers

- Between 1980 and 2022, U of T researchers published 4,577 articles — the most quantum publications in Canada.
- U of T-led quantum research is the most influential in Canada (32.65 citations per paper on average.)
- 35 faculty members focused on quantum computing, communications, and cryptography, sensing and metrology, imaging, materials, and simulation.

Citation impact of quantum research from leading universities, 2017–2021

Institution	Documents	Citation Impact (citations/papers)	% Industry Collaborations
Harvard University	1,783	39.27	4.60
Massachusetts Institute of Technology (MIT)	2,347	34.64	5.71
Stanford University	1,686	34.15	4.86
Nanyang Technological University	1,487	33.33	2.49
University of Toronto	1,033	32.65	4.26
Princeton University	1,370	32.43	6.06
University of California Berkeley	1,614	31.67	7.06
California Institute of Technology	1,342	31.16	5.74
Lawrence Berkeley National Laboratory	1,255	31.11	3.35
Soochow University - China	1,301	30.83	1.23
# 46 University of Waterloo	1,262	18.71	5.55
# 44 Canada's U15 Universities	5,788	19.56	2.89

Data sources: *Clarivate Web of Science, accessed 1/12/2023. Responsive to Topic search = quantum or "photon entangle*" or Hamiltonian or "coherent control")) OR WC=(Quantum Science & Technology). Citation impact is defined as the average citations per paper published. The importance of a research paper is linked to how much it is cited by others and used in their own work, therefore citation impact is a metric of scientific importance.*

- 499 grants to support research on quantum challenges.
- A foundation for advanced research in Canada with $1.45 billion in research funding for U of T and its partner hospitals.
- Ranked 1st in Canada and 12th in research in the world by the Times Higher Education World Universities Rankings.

Training and Talent

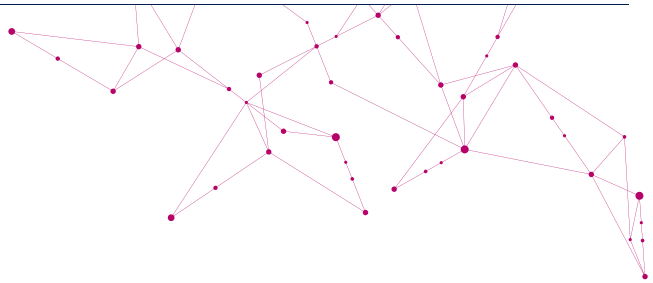
As with artificial intelligence, the ability to offer master's and PhD level training and credentials is critical for growth in the sector. At the graduate level, the University offers a specialized program, the Master of Science in Applied Computing—Quantum Computing. In addition, U of T boasts world-class research strength in foundational fields required to advance quantum discovery, including physics, chemistry, mathematics, and computer science, as well as the No. 1 engineering department in Canada.

Commercialization

U of T is recognized as a leader in translating cutting-edge research into innovation, startups, and jobs, a profile that is demonstrated in the quantum sector as well:

- $2 Billion raised by more than 600 U of T startups over the past decade.
- #1 rank in research-based startups among Canadian universities.
- Public-private partnerships, including with the Fujitsu Co-Creation Lab and the National Networks of Excellence and Cisco.
- 31 patents over the last 20 years.
- In the last decade, at least 12 quantum companies have been founded by U of T alumni and faculty and have raised more than $300 million.

Quantum leaps from U of T's quantum startups



Canada's quantum opportunity will be shaped by the extent to which it can support the creation of quantum companies and adoption of quantum technologies across industries. These companies are working actively with academic researchers to develop new products and open new markets.

Xanadu

Since its inception in 2016, Xanadu has been on a mission to build quantum computers that are useful and available to people everywhere. CEO Christian Weedbrook began the company in Toronto after a postdoctoral fellowship in physics at the University of Toronto. Xanadu's photonic approach to building quantum computers is unique and advantageous for several reasons. Most importantly, using photonics enables the leveraging of modern chip manufacturing facilities, the application of optical components developed by the pre-existing telecommunications industry and the use of fibre optics to network photonic chips together. Such networking is needed to reach and exceed one million qubits, the scale at which useful applications can be accessed. In November 2022, Xanadu reached a company valuation of $1 billion (U.S.) after its latest round of financing ($100-million U.S.)

www.xanadu.ai

Zapata Computing

A quantum computing software company, Zapata helps industry compose and conduct quantum-enabled workflows. Among the co-founders is Alán Aspuru-Guzik, a Professor of Chemistry and Computer Science at U of T, Canada 150 Research Chair, and the Canada CIFAR AI Chair at the Vector Institute for Artificial Intelligence. To date, the firm has raised $67.4 million (USD) and employs 100 people, with offices in Toronto, Boston, London and Tokyo.

www.zapatacomputing.com

OTI Lumionics

The company's co-founders, Michael Helander and Zhibin Wang, completed their PhDs from U of T's Faculty of Applied Science and Engineering and participated in CDL's Quantum Stream. OTI Lumionics is developing advanced electrode materials to build transparent displays and lighting for next-generation consumer electronics and automotive. As of 2020, OTI Lumionics raised $3 million (USD) and employs 45 people.

otilumionics.com

Agnostiq

Co-founder and COO Elliot MacGowan completed his MBA at U of T and participated in CDL's Quantum Stream. Agnostiq develops software tools that make quantum and high-performance computing resources more accessible to enterprises and developers. Headquartered in Toronto, the firm employs 17 people across North America and has raised $2.71 million.

agnostiq.ai

Quantum Bridge Technologies (QBT)

Co-founder and CEO Mattia Montagna is currently a Postdoctoral Fellow at U of T. Co-founder and CTO Hoi-Kwong Lo is a Professor in the Department of Electrical and Computer Engineering and Department of Physics. Quantum Bridge Technologies provides a suite of quantum-safe communication solutions. The firm participated in CDL's Quantum Stream and entered the UTEST program. Based in Toronto, the firm employs 12 people and received financial backing from Good News Ventures.

qubridge.io

Left, Xanadu's offices in downtown Toronto, courtesy Xanadu Quantum Technologies Inc., as well as cover photo.

Conclusion

While technological revolutions are rare, quantum science and technology represent an important new frontier in discovery and economic opportunity. Emerging from a nexus of several disciplines, including mathematics, computer science, physics, chemistry, and engineering, this field offers a new lens to analyze, measure, and compute the world. The introduction and deployment of quantum computation, communication and sensing hold tremendous promise to benefit numerous industries from finance to advanced manufacturing and health.

Drawing on the model of advancing artificial intelligence deployed through the Pan-Canadian Artificial Intelligence Strategy, Ontario and Canada once again have an opportunity to lead in the development and commercial deployment of an advanced technology. Canada's research ecosystem is advancing the technological potential of quantum science and supporting companies that are developing quantum hardware and software, as well as the firms that will benefit from these products.

The concentration of resources in several national quantum hubs can provide a focus for investments that recognize and match the scale of other countries' support. Strong support will guide collaborations among researchers and industry, increase capacity for industry to integrate quantum technologies, and increase training of a quantum-literate workforce who will drive development of this emerging and exciting technology.

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"Quantum science and technology hold tremendous promise to improve the lives of all Canadians. The talent and research at the University of Toronto and in all of Canada's quantum hubs are opening the door to new applications and greater security across our most dynamic economic sectors. Now is the time to act and invest and ensure that Canada is not a follower but a leader in defining this new frontier."

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