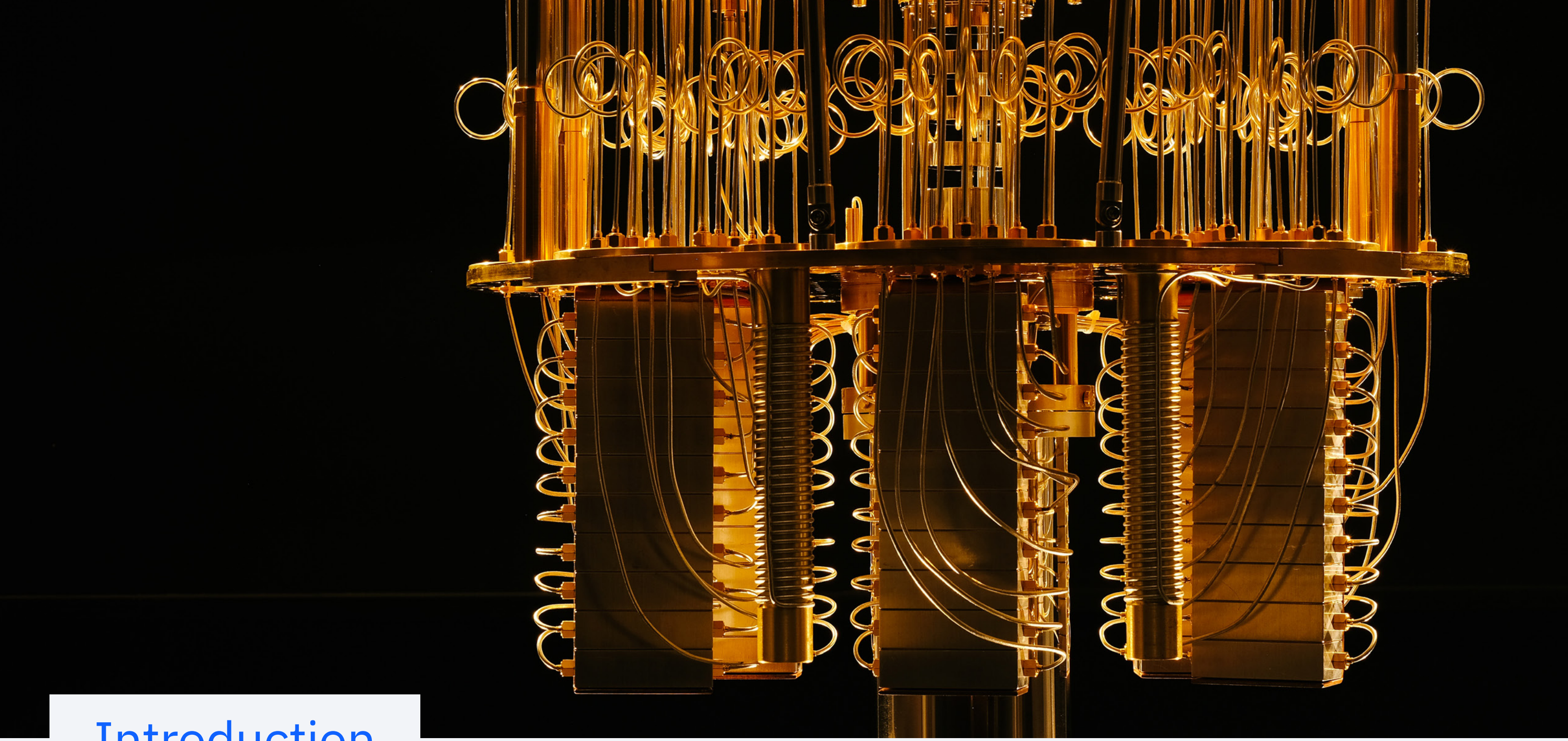
Driving Canada's Industrial & Academic Eminence towards a National Quantum Strategy

IBM



Introduction

Quantum computing is the first fundamentally new approach to computing in decades. While the first quantum revolution gave humanity new insight into the rules that govern the physical world, the second quantum revolution is applying these rules to develop new technologies that the industry anticipates will eclipse the processing power of even today's most powerful supercomputers. In the shorter term, there is great optimism that hybrid classical/quantum computing will deliver real value to business and society at large.

In Budget 2021, Canada committed $360 million to launch a National Quantum Strategy to achieve three overall objectives: amplify Canada's significant strength in quantum research; grow domestic quantum-ready technologies, companies, and talent; and solidify Canada's global leadership in this area.[1]

Canada is currently one of the world's leading nations in quantum research, ranked 5th in the G7 in total expenditure on quantum science, and 1st per capita.[2] However, as quantum technology nears the inflection point of delivering real commercial value, global competition is intensifying to capitalize on this burgeoning industry.

To ensure the National Quantum Strategy leads to successful outcomes, there must be renewed collaboration by all stakeholders — government, industry, and academia — in the Canadian quantum information science ecosystem. It is critically important that Canada focuses these efforts on tangible short and medium-term outcomes, as well as long-term research health and viability. By doing so, stakeholders will ensure that Canadian industry is enabled and empowered to compete in the new quantum era and to leverage our academic leadership in this emerging field.

This paper will discuss the economic opportunity of quantum computing and offer guidance on how Canada can position itself as a global leader in this technology. The authors do not intend to provide an exhaustive overview of available quantum computing programs, training, or funding. Rather, the paper is intended to evoke discussion about the best path forward for Canada in the quantum computing industry.

Quantum computing 101

"Quantum technology is at the very leading edge of science and innovation today, with enormous potential for commercialization. This emerging field will transform how we develop and design everything from life-saving drugs to next generation batteries, and Canadian scientists and entrepreneurs are well-positioned to take advantage of these opportunities. But they need investments to be competitive in this fast-growing global market."

- Budget 2021

All computing systems rely on a fundamental ability to store and manipulate information. Today's classical computers manipulate individual bits, which store information as binary 0 and 1 states. Millions of bits work together to process and display information with the speed familiar on smart phones, laptops, and servers in the cloud.

In contrast, quantum computers tap into quantum mechanical phenomena to manipulate information. To do this, they rely on quantum bits, or qubits. Unlike a bit that has to be a 0 or a 1, a qubit can be in a combination of states. By applying the principles of superposition, entanglement, and interference, an exponentially large number of compute states can be explored as the number of qubits increases. As the technology improves, alongside the increase in the number of qubits, we will reach quantum advantage, the point where certain information processing tasks can be performed more efficiently or cost effectively on a quantum computer, versus a classical one, alone.

Quantum computers are not a replacement for classical computing systems. They complement classical systems with a promise to resolve intractable problems that are too time-consuming or impossible to solve when using classical computers. The evolution of quantum computing is expected to create new opportunities in scientific discovery, and to eventually disrupt critical areas of technology such as cybersecurity and encryption.[3] In fact, this disruption is the reason for industry to implement "quantum safe" cryptography schemes *today*. To mitigate these risks, IBM has developed a clear strategic agenda that includes the research, development, and standardization of core quantum-safe cryptography algorithms as open source tools. In the coming years, these tools will be standardized to protect against the encryption exposure created by quantum computing.

Not all quantum computers are created equal, nor do they solve the same classes of problems. The ultimate goal is a fully fault-tolerant universal quantum computer that can handle important classes of business and scientific problems exponentially faster than a classical machine.

Today, companies such as IBM are developing computing systems, which although still noisy, are steps on the path towards fault-tolerant universal quantum computing.[4]

By 2023, IBM expects to demonstrate a new generation of quantum systems that have a clear path toward quantum advantage – when quantum computers working closely with classical computers can address problems better than any classical system can alone.

Quantum: Economic Impact for Canada and the World

Discovery is a driving force of science, business, and economic prosperity. High performance computing, artificial intelligence, hybrid cloud, and — soon, quantum computing — will accelerate discovery in science and business, while expertise in these technologies will cultivate the workforce of the future.

When combined with other emerging technologies, quantum computing has the potential to speed up the discovery of new materials that will address significant global challenges. Specifically, technology can be used to reinvent the materials design process to find solutions to challenges such as fostering good health and clean energy, as well as bolstering sustainability, climate action, and responsible production.

New materials or novel uses of existing ones are likely to help address challenges such as capturing carbon dioxide from the overburdened atmosphere and storing it safely, mitigating climate change; finding more sustainable ways to grow crops to feed surging populations while reducing carbon emissions; rethinking batteries and energy storage; and developing more sustainable electronic devices and better antivirals.[5]

In a 2017 economic analysis conducted for the National Research Council of Canada, it was estimated that by 2030, the domestic quantum technology industry could be worth $8.2 billion and employ 16,000 people. By 2040, when quantum technology is expected to reach 50 per cent adoption, it was estimated quantum could grow into a $142.4 billion industry and sustain 229,000 jobs.[6]

To date, the federal government has invested more than $1 billion in quantum computing research and development (R&D), while provinces such as Quebec, Ontario, British Columbia, and Alberta have made early investments in quantum research organizations as the technology advances towards application. It is worth noting that billion-dollar quantum R&D programs have also been announced by the United States, China, the European Union, and India.[7]

As the quantum computing industry is still in early development, there are no easy predictors to model the total economic impact of Canadian academic and industry capacity, leadership, and skills in quantum technologies. However, these industries are well-represented in Canada, and it is a reasonable expectation that quantum computing investment will have a strong economic impact.

Canada’s steps to quantum success

In Budget 2021, the federal government noted that the National Quantum Strategy will be designed to amplify Canada’s significant strength in quantum research; grow domestic quantum-ready technologies, companies, and talent; and solidify Canada’s global leadership in this area.

A recent global analysis notes four policy measures are commonly deployed within national quantum strategies:

- establishing centres of excellence or innovation hubs;
- making targeted calls for proposals or competitions;
- providing direct funding for special projects of national significance; and
- providing government investment or venture capital for startups.[8]

Canada has done well to deploy some of these policy measures early, despite the historical absence of a coordinated national quantum strategy. As a recent CIFAR report highlighted, 17 countries including the US, Japan, Germany, and the UK have some form of national initiative or strategy to support quantum R&D.[9] A further three, including Canada, have strategies that are in various stages of development.

> *“Quantum technology and artificial intelligence are key parts of our government’s plan to make our post-pandemic economy stronger than ever.”*
>
> *– Hon. François-Philippe Champagne, Minister of Innovation, Science and Industry, March 11, 2021*

In the US, the passage of the National Quantum Initiative Act (2018) was a seminal moment for quantum information science, and a clear recognition of the critical importance of quantum in the security and prosperity of the world’s largest economy.[10]

Achieving rapid commercial leadership in quantum computing requires six key actions over the next three to five years. In the near term, Canada must focus on three areas:

1. **Highly Qualified Personnel:** Canada must attract and retain a critical mass of trained highly qualified personnel in the quantum computing field including highly skilled foreign students, scientists, and engineers through acceleration of appropriate academic training and funding. To further this effort, immigration policies must be flexible to allow for the accelerated inflow of quantum capable workers.

   Academia, guided by targeted calls for proposals or competitions that leverage government funding, should design quantum training opportunities that consider the best near-term commercial applications of quantum computing technology, in order to cultivate a research ecosystem that appeals to a wide spectrum of highly skilled personnel.

2. **Hybrid computing expertise:** In this case, we define hybrid computing as the combined use of classical and quantum computing approaches. Canada must develop hybrid classical/quantum computing expertise, where improved high-performance computing (HPC) infrastructures are leveraged to transition research and industry towards quantum applications, as these capabilities increase.

   Continuous advances in HPC are already helping to accelerate discovery, while the COVID-19 pandemic has highlighted the importance of scientific discovery for the design of new medicines, vaccines, and pharmaceutical products. High performance computing, artificial intelligence, quantum computing, and hybrid cloud technologies are collectively converging to accelerate discovery in science and business and cultivate the workforce of the future.

One innovative example of this technology convergence is the IBM Discovery Accelerator at the Cleveland Clinic, which includes the installation of an IBM Quantum System One on the medical centre's main campus to enable new medical breakthroughs and provide access to quantum technology for universities, high schools, and the government, with particular focus on creating the future quantum computing workforce.[11] This model can be replicated in Canada with the right partnerships to mutual benefit.

3. **Collaboration**: Academia has a unique role to play in educating the next generation of scientists and citizens. But these institutions must develop innovative teaching partnerships among disparate disciplines within academia, between academia and industry, and between academia and government laboratories to create flexible curricula and industry-relevant quantum educational and training programs.

   By building practical quantum collaborations between leading private sector technology companies, academia, and government laboratories, we can create sustainable R&D ecosystems driven by a focus on near-term commercial research and application. Government-funded provincial organizations have been established in the past few years alone with the intent of enabling industry-academia partnerships for quantum computing. Early examples of these collaborations include the Quantum Algorithms Institute (QAI)[12] in British Columbia and the Institut Quantique[13] at the Université de Sherbrooke in Quebec, where the IBM Quantum Network recently established its first Canada-based Quantum Hub to engage industry and research partners. There is ample opportunity within this ecosystem for the federal government to further act as an enabler of quantum R&D to enhance commercial application.

   Rudimentary quantum education should also be integrated into curriculum starting at the secondary level and designed with industry-recognized, skills-based credentials in mind and be offered widely at the post-secondary level, in partnership with industry.

In a second phase, consolidation of Canada's leadership position in quantum information science will be achieved by:

4. **Manufacturing:** Canada should support quantum-enabling technologies and photonics, including the domestic manufacturing of critical advanced hardware and components, thereby securing important ingredients of the hybrid computing and quantum supply chain. Additionally, manufacturing these critical hardware components for quantum technology will foster increased international collaboration amongst allies.

   CIFAR notes that strengthening the supply chain for components of quantum technology (such as the fibres and satellites needed for a quantum internet, or the chip fabrication and manufacturing infrastructure for quantum computers), is a central strategic policy goal of many countries in their development of quantum computing.[14]

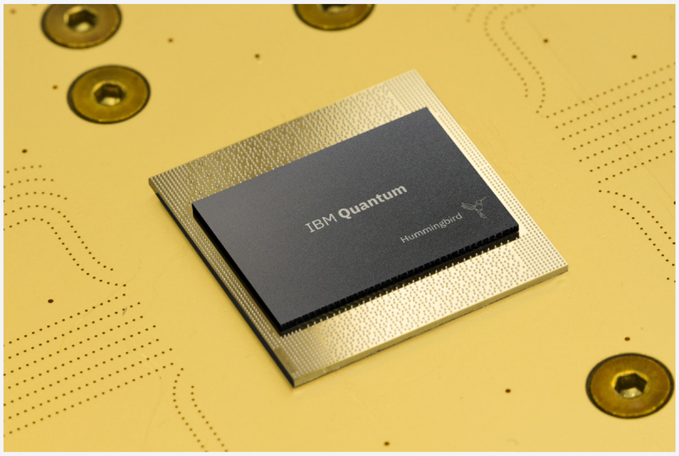
   Canada's national quantum strategy should focus on nurturing the existing hardware ecosystem and find innovative ways to establish long-term partnerships with enterprises to ensure domestic manufacturing is bolstered.

5. **Hosting:** Hosting world-class quantum computers in secure facilities on Canadian soil will provide dedicated, broad access to academic and government researchers, industry, and allow quantum start-ups to scale their companies. IBM's first international deployments of its Quantum System One at data centres in Germany[15] and Japan[16] are significant investments that support the quantum strategies of these countries. By facilitating quantum computing access through hosted systems, Canada could strengthen its leadership in quantum science, business, and education and benefit from a stronger position to attract and retain highly skilled talent as global competition intensifies.

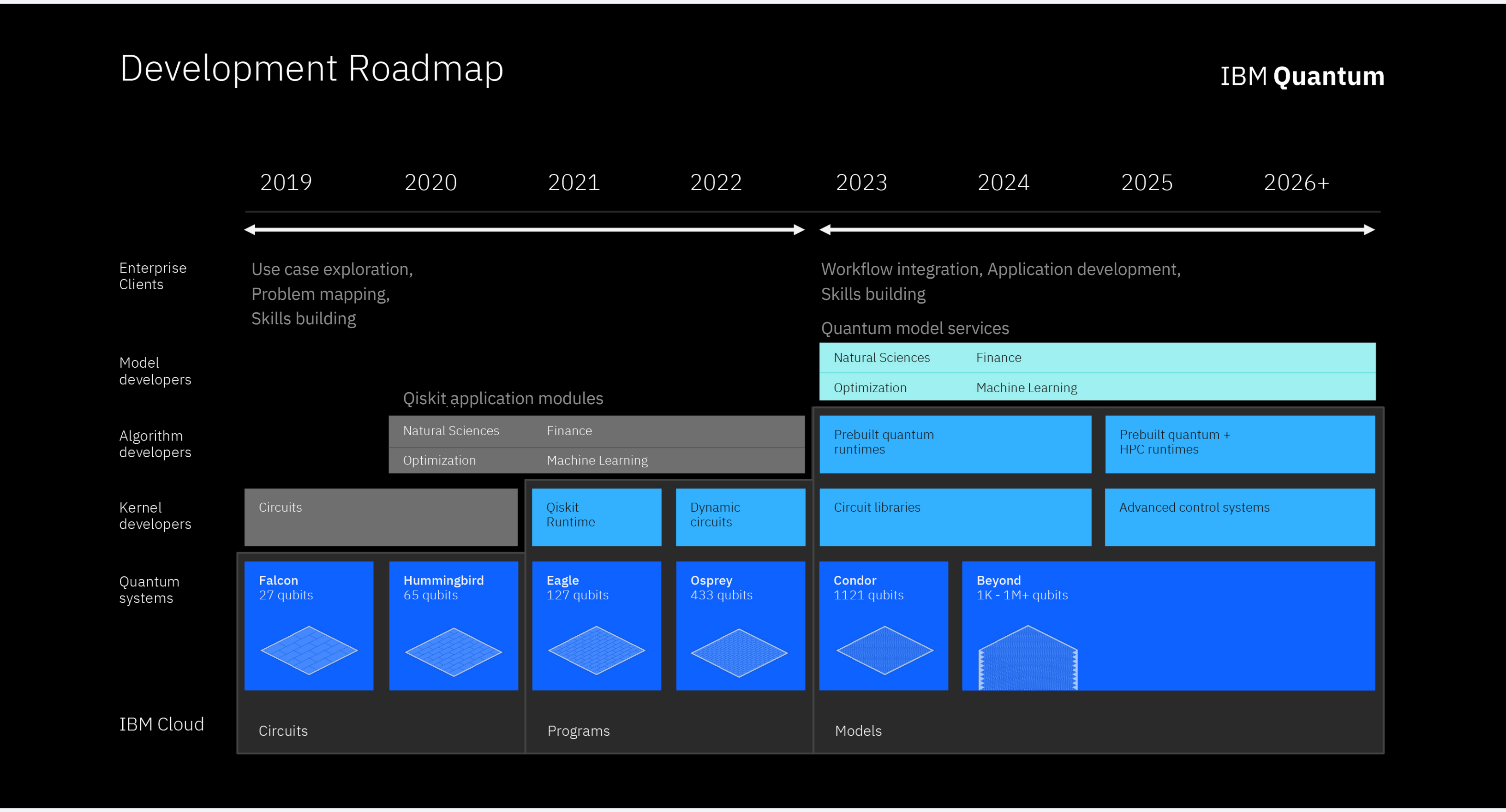
6. **Broad Ecosystem of Quantum Enabling Technology:** Quantum software and algorithm development, middleware, and specific industry applications that bring competitive advantage will thrive once the foundations of the quantum landscape are in place. A coordinated ecosystem would allow for the rapid dissemination of quantum computing capabilities across industries through pan-Canadian ecosystems and partnerships.

Development of points 2 through 6 — with emphasis on broad access to world-class quantum computers — will create a feedback loop that amplifies the development of highly qualified personnel and creates long-term, high-value Canadian jobs and skills-building opportunities.

While not exhaustive, these action items will help ensure Canada optimizes its ability to train a quantum-ready workforce nationwide.



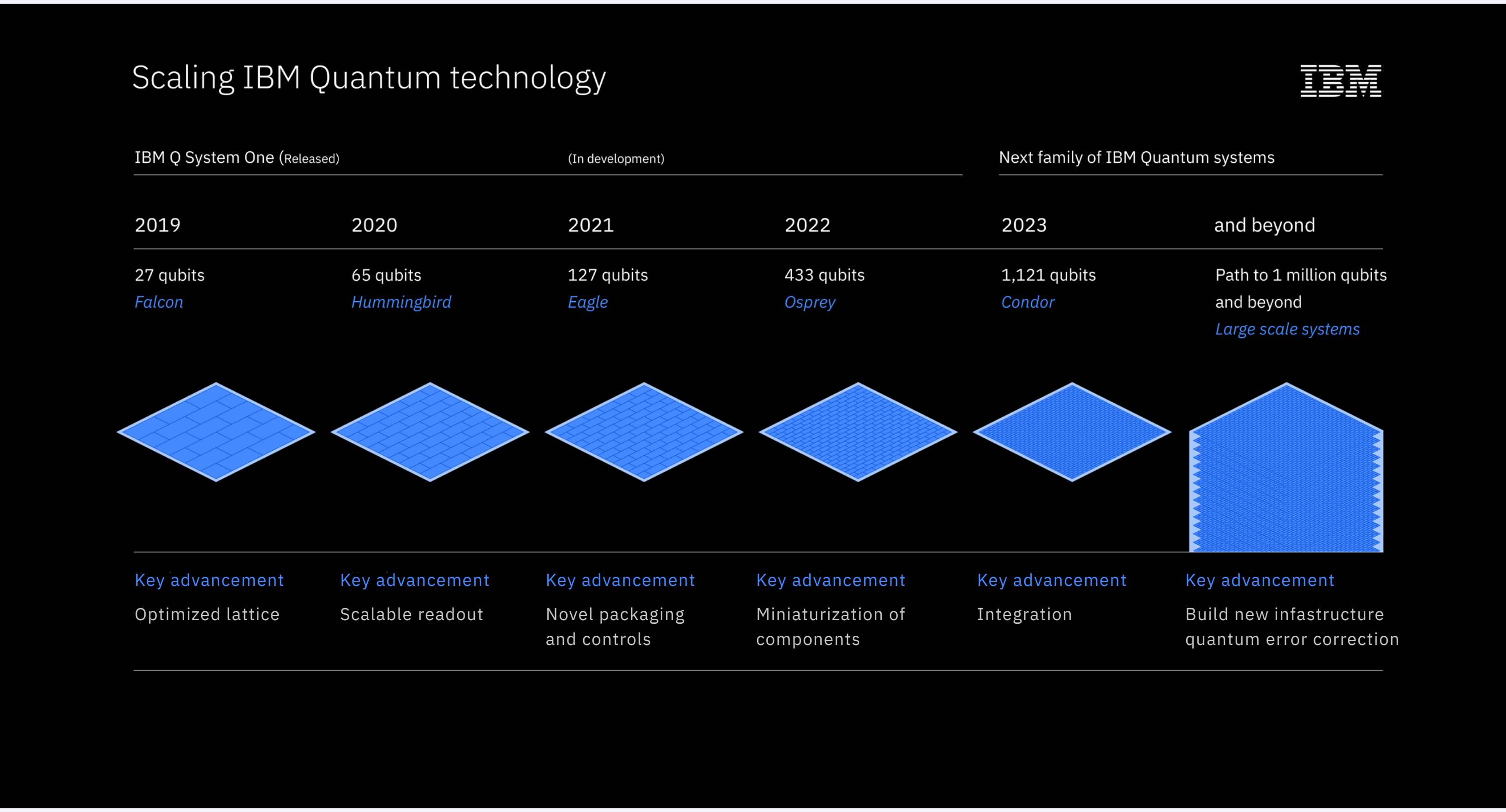
Addressing the Digital Skills Gap: Additional Resources



IBM Quantum software development roadmap.

Open source access and adoption is how an ecosystem of developers, scientists, educators, and professionals across different industries will get "Quantum Ready" for this next generation of computing. Scaling a global community with the right skillset is key to advancing quantum computing for science and business, and countries that choose to invest and engage early on will derive an economic advantage in doing so. A National Quantum Strategy will also require the development of a better understanding around the deployment, monitoring, and assessment of emerging approaches to digital skills identification, development, and employment.[17]

To help accomplish this global effort, IBM became the first company to put a quantum computer on the cloud in 2016. IBM Quantum Composer and the IBM Quantum Lab[18] have since built up an active community of more than 325,000 users, who have run hundreds of billions of circuit executions (more than two billion per day), on real hardware and simulators, which have led to the publishing of more than 500 third-party research papers. Underpinning this effort is an open source software development kit called Qiskit,[19] which allows programmers to accelerate the development of quantum applications by providing the complete set of tools needed for interacting with quantum systems and simulators. Qiskit allows for easy research and development for specific industry use cases that have the highest potential for quantum advantage. Qiskit has been downloaded more than 650,000 times to date.



IBM Quantum software development roadmap.

To provide guidance to all stakeholders on quantum development, IBM has also made public a Quantum Development Roadmap[20] which points towards our larger mission: to design a full-stack quantum computer deployed via the cloud that anyone around the world can program.

Industry training resources like those listed here allow for greater competency and lower-barrier adoption of quantum skills that Canada requires to fuel the quantum computing economy of tomorrow.

Conclusion

Each element of quantum computing requires specific skills and provides unique opportunities for Canadian technology start-ups, businesses across disciplines, and researchers with the outcomes affecting society as a whole.

A Canadian National Quantum Strategy should enable the rapid expansion of collaboration to achieve a critical mass of quantum technology and foster quantum-ready skills that will ensure Canada can compete globally. Exploring practical applications and future use cases for quantum computing requires cohesive partnerships between industry, academia, and government.

As we work together to prepare the quantum-ready workforce of tomorrow, we must all do our part to enable access to this emerging technology and to secure Canada's quantum leadership on the global stage.

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Produced in Canada
May 2021