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Quantum computing: A new frontier in techno-nationalism

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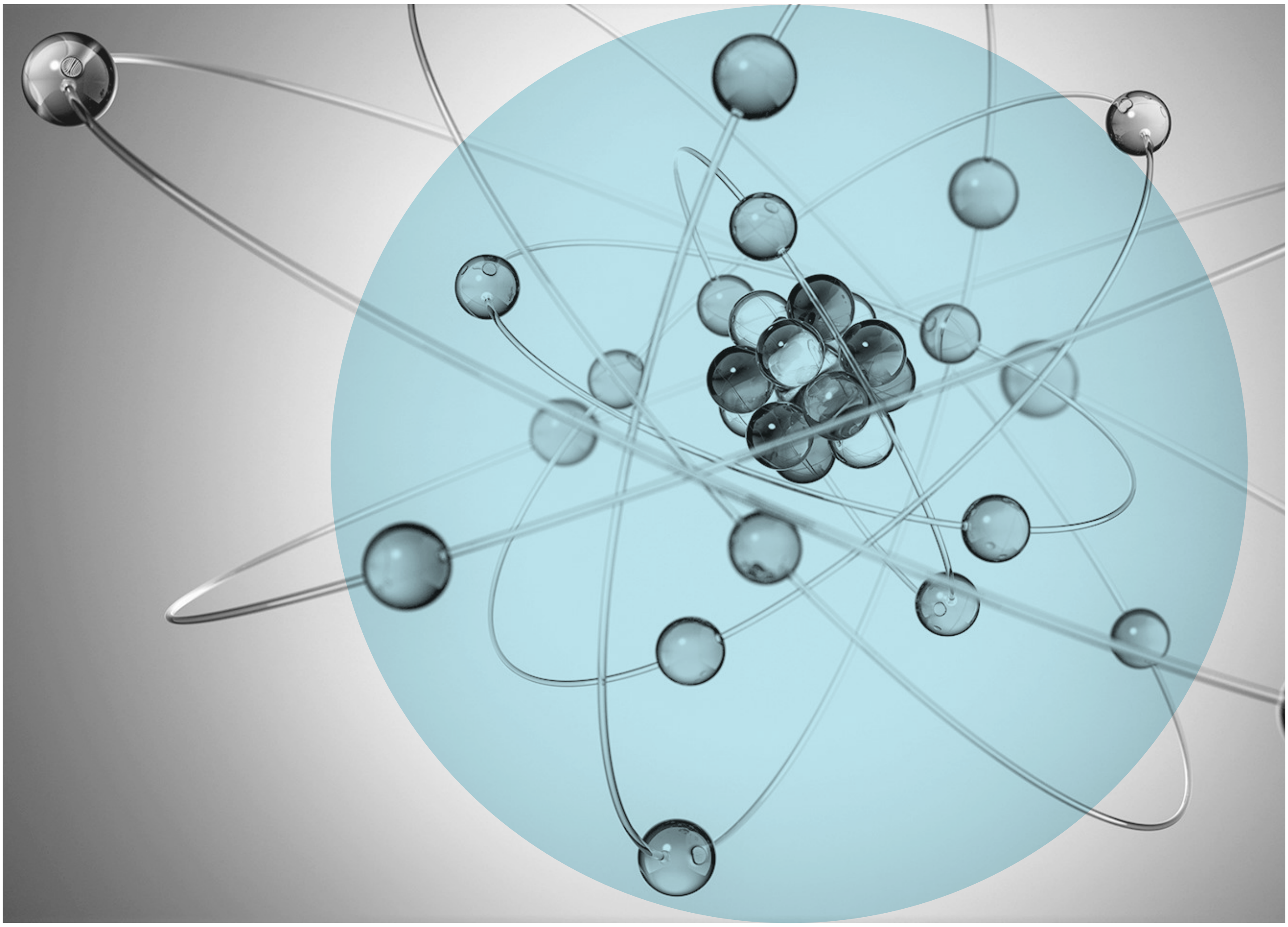

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Introduction

The end of Moore's Law

The age of modern computing has produced remarkable innovations across entire industries, a phenomenon that has been driven largely by semiconductors.

Since 1965, the number of transistors on a semiconductor (also referred to as "microchips" or "chips") have doubled approximately every two years, making microchips faster, smaller, and more efficient. Simultaneously, in each of these two-year timespans, the cost of computers has been cut by roughly one half.

This marvel, known as Moore's Law, has held true for more than four decades. Now Moore's Law has reached its end.

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Semiconductors can no longer accommodate increased numbers of transistors (known as "bits") on surface areas that have shrunk to the size of an atom. With the advent of the two-nanometer microchip, which is *two-billionths* of a meter, silicon-based semiconductors have hit the proverbial wall. Another revolutionary breakthrough is needed to continue advancement in Artificial Intelligence (AI) and other industries of the future.

The rise of quantum computing

Quantum computing (QC) promises to provide the answer. It operates on a much smaller scale than classical bit-based computers, but its computational power is exponentially greater than that of the silicon-based microchip.

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This technology is still nascent but advancing quickly. Although it will not replace contemporary digital computers for everyday usage, quantum computing is solving highly complex computations that the world's most powerful supercomputers cannot solve.

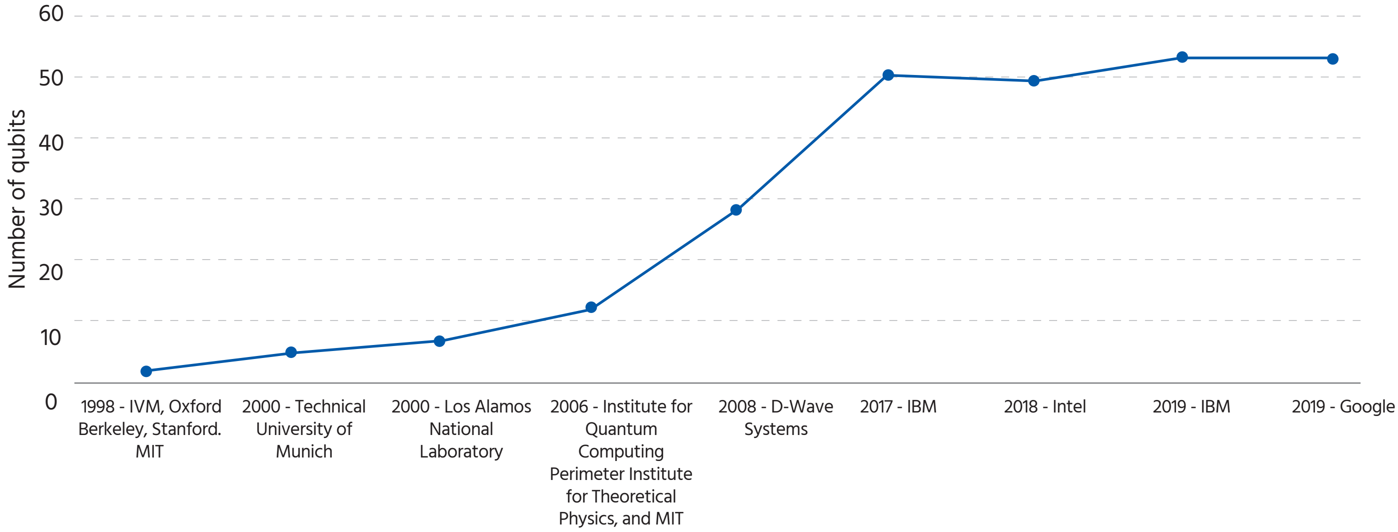
In 2019, scientists at Google announced a breakthrough. A quantum processor based in Santa Barbara had achieved "quantum supremacy", the scientists declared. Sycamore, as the computer is called, had solved in 200 seconds a numeric computation that would have taken the world's most powerful super-computer 10,000 years to solve.[1]

Not to be outdone, soon IBM announced that their classical bit-based technology could solve the same problem in *2.5 days*. Google responded by acknowledging that perhaps a more realistic timeframe would be about a week.

Less than a year later, a team of Chinese physicists at the University of Science and Technology at Hefei announced their own breakthrough.[2] A photon computer, claimed the scientists, performed a mathematical computation to solve in 200 seconds the so called "boson sampling problem", an operation that would have taken a classical supercomputer *2.5 billion years* to solve.[3]

These developments represent a major technological milestone. Just as the successful splitting of a tiny invisible atom resulted in nuclear fission and the unleashing of unimaginable amounts of energy, quantum computing's nano-scale technology has ushered in a new era.

Figure 1 – Number of qubits achieved in quantum computers from 1998 to 2019[4]



Note: In 2021, the number of qubits is believed to be approaching 70-80.

Source(s): CB insights; IBM; Googles

Quantum computing could reshape innovation and competition in virtually every field, from cryptography and chemistry to manufacturing, finance, and logistics. Consequently, quantum science will play a key role in transforming the global economy and global trade.

The full impact of quantum technology may not be felt for years. Yet state and non-state actors must begin now to understand and successfully harness the power of the "qubit" – or risk being dominated by those who do.

Quantum computing and techno-nationalism

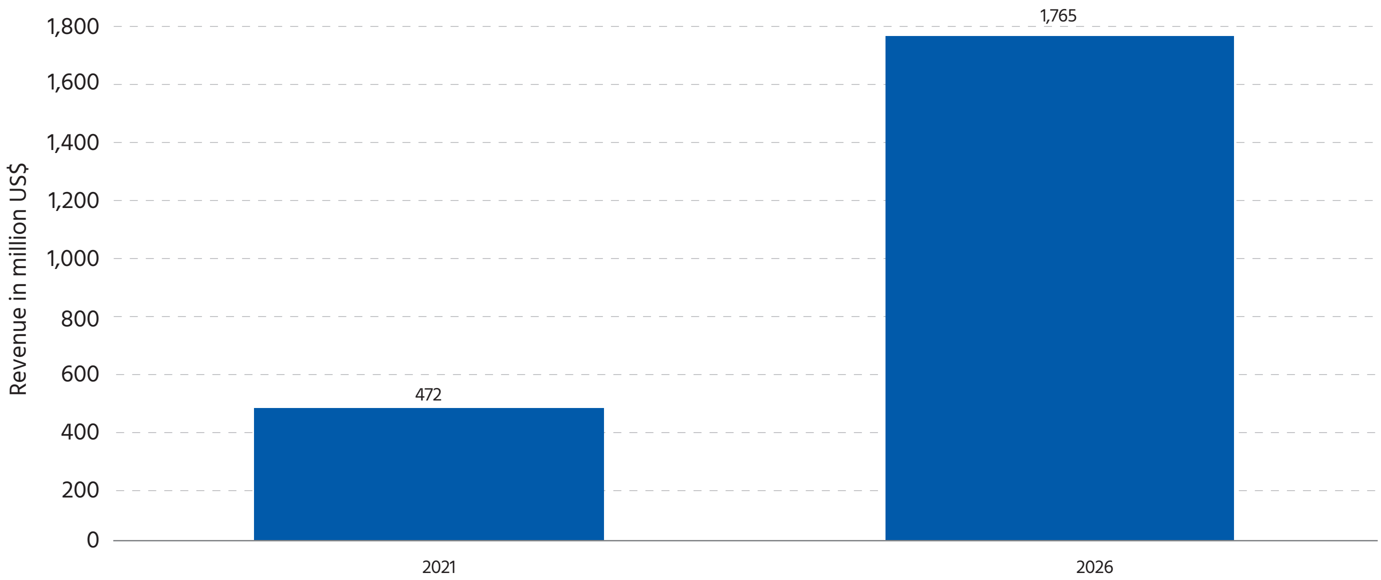
Quantum computing has increased the stakes in the US-China technology competition.

Quantum computing has increased the stakes in the US-China technology competition. As we have seen from previous Hinrich Foundation reports, techno-nationalism is a neo-mercantilist mindset that links a nation-state's technological prowess with its economic prosperity, national security, and socio-political stability.

Semiconductors have been at the heart of Washington and Beijing's techno-nationalist hybrid cold war and have resulted in the strategic decoupling and geo-fencing of key supply chains. Funding initiatives to spark home-grown innovation are also in play. Similar to semiconductors, the race for quantum supremacy will draw upon a feedback loop involving the technology sector, economic and financial institutions, political bodies and the military-industrial complex.

Caught in the middle of this feedback loop are universities and research institutions, individual scientists, investors, academics, NGOs, and political figures.

Figure 2 – Forecast size of the quantum computing market worldwide: 2021 and 2026 (in million US$)[5]



Source(s): MarketsandMarkets

Overview

This study is not a technical analysis or a scientific examination of quantum computing. Instead, it is a study of the latest general developments viewed through the lens of techno-nationalism and geopolitics.

The report is divided into three sections.

Section I: What is quantum computing and why does it matter?

We begin by providing an essential explanation of the basics of quantum computing and how it differs from classical computing, primarily because of the phenomena of "qubits", "superposition," and "quantum speedup." Next, we highlight QC's key uses and which industries and sectors will be most affected, and, finally, the strategic implications for both state and non-state actors.

Section II: The US-China innovation race and the quantum computing landscape

China leads the world in the number of patents related to quantum technology. Meanwhile, the US leads in hardware and software patents for quantum processing.

China leads the world in the number of patents related to quantum technology. State-backed actors in China have focused heavily on hardware and software for communication and cryptography. We examine one particular application called Quantum Key Distribution (QKD) which uses bursts of photon transmissions, bounced off satellites, to create virtually un-hackable cyber-secure communication networks.

Meanwhile, the US leads in hardware and software patents for quantum processing. We examine how markets and non-state actors in the US and China are operating in different kinds of environments and how strategic partnerships and government initiatives are shaping the global QC landscape. Finally, we look at how the world's best-funded private companies and tech start-ups are influencing the sector.

Washington has resorted to restrictions and export controls to weaponize QC supply chains, and to ring-fence R&D through strategic partnerships and techno-diplomacy.

Section III: Techno-nationalism and the future of quantum computing

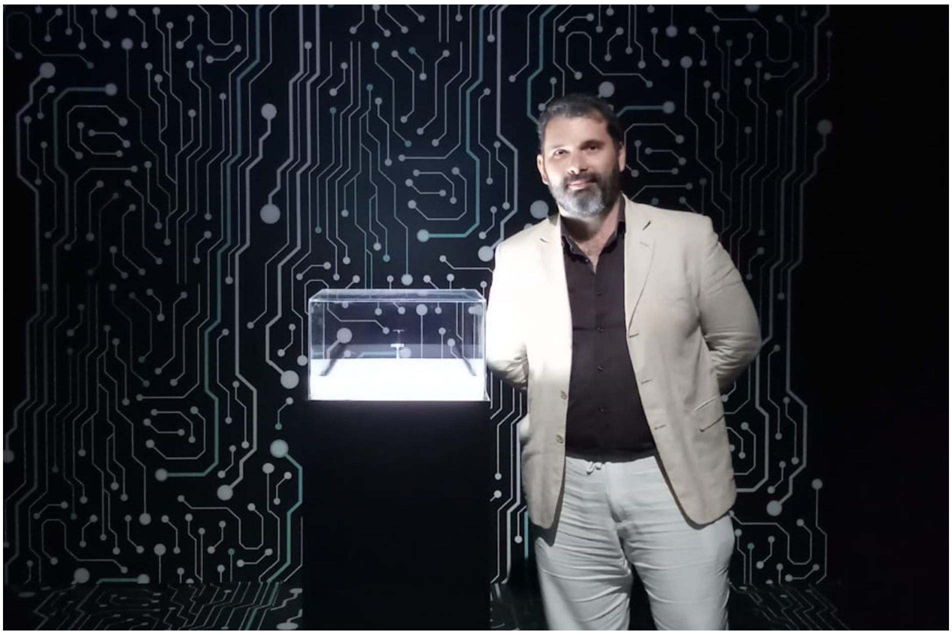
The same techno-nationalist pressures shaping the semiconductor sector will alter the international quantum computing landscape. Washington has resorted to restrictions and export controls to weaponize QC supply chains, and to ring-fence R&D through strategic partnerships and techno-diplomacy.

Here, we examine which stakeholders could be most affected, including academic institutions and individuals involved in international research. We conclude with a look at how ethics and rule-frameworks are needed to prevent the misuse and monopolization of quantum power by a few actors.

Discussions with a quantum technology pioneer

The author's analysis throughout this report has benefitted from a series of discussions with Dr. Dimitris Angelakis, a pioneer in quantum physics and quantum algorithms. Since completing a PhD at Imperial College, London, in 2001, and a subsequent research fellowship at Cambridge University, Dr. Angelakis (pictured below) has worked with the world's pre-eminent experts, including at Google. His contributions to Google's early ground-breaking processors won him the Google Quantum Innovation Award in 2018. The prototype chip for the project was donated to Singapore's Arts and Sciences Museum. Currently Angelakis is a professor and group leader at the Centre for Quantum Technologies at the National University of Singapore.

Dr. Angelakis is also a professor at the Technical University of Crete, Greece, and the founder and chief scientist at a quantum computing consulting start-up.[6]



Dr. Dimitris Angelakis, at Singapore's Art and Science Museum, posing with the prototype of the quantum chip used in the collaboration between Angelakis and Google in 2017.

Dr. Angelakis can be contacted directly at dimitris.angelakis@qubit.org.

What is quantum computing and why does it matter?

The laws of physics draw a distinct boundary between classical and quantum computers. Traditional computer microprocessors perform a series of "either/or" calculations based on strings of "1"s and "0"s called "bits".

In classical digital computing, computer scientists program different kinds of logic "gates" to instruct how and when these bits work together, and when either a 0 or a 1 will be used in computational sequences.[7] By stringing together millions, even billions, of these binary sequences, a classical computer can follow complex algorithms and perform highly advanced computational functions.

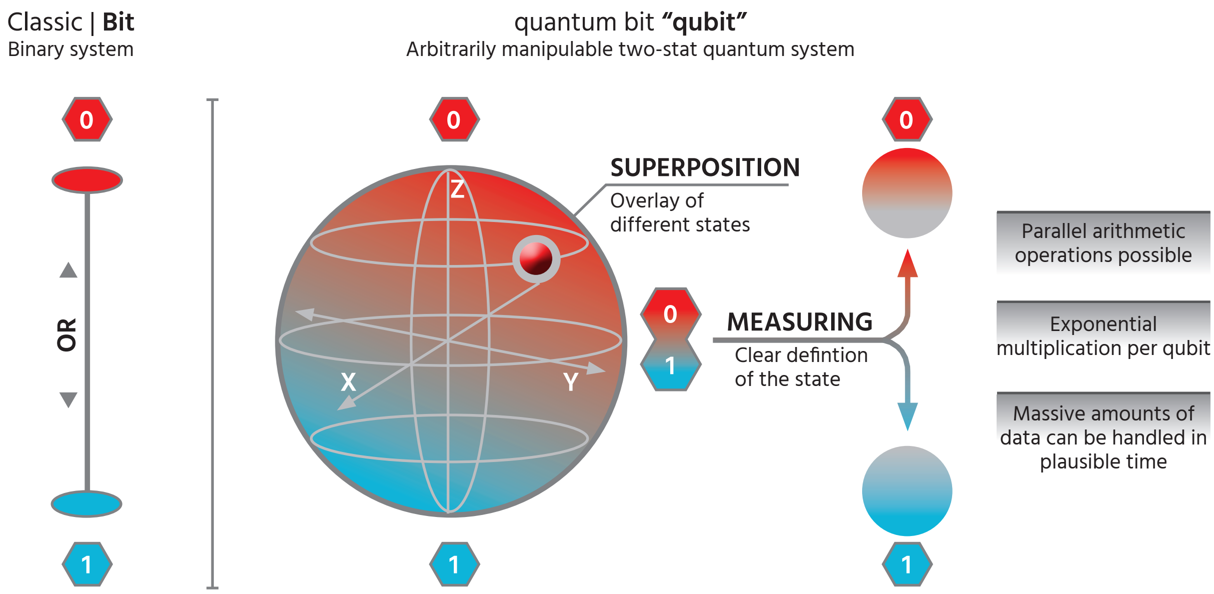
Quantum computing operates on a much smaller scale than classical computing, using quantum mechanics to harness the behaviour of atoms, photons, and electrons.

"Qubits" and a new era of computing

Quantum computing operates on a much smaller scale than classical computing, using quantum mechanics to harness the behaviour of atoms, photons, and electrons. Instead of bits, quantum computing utilizes quantum-bits, known as "qubits." Here is where things begin to get very strange.

The first major difference between a bit and qubit is the phenomenon known as "Superposition". In classical computing, a bit can only be a "0" or a "1" at any given time. A qubit, however, can be both a 0 and 1 simultaneously. In quantum computing, therefore, electrons and photons assume states that would be mutually exclusive in classical computing, which gives quantum computing a huge advantage in computing power.

Figure 3 – How a quantum computer works[8]



Quantum computers work with qubits instead of with bits, enabling them to carry out considerably more complex calculations.

Superposition leads to a second fundamental difference between bits and qubits, which is the phenomenon of "Quantum Speedup." Because of superposition, each qubit doubles computing power as it is added to a string. For example, 2 qubits equal four possible simultaneous states, 3 qubits equal 8, 4 equal 16 and so on, until, when compared to the binary limitations of bits, it becomes impossible for classical computers to keep pace with Quantum Speedup. "The quantum superposition combined with the phenomenon known as "quantum interference" allows for quantum algorithms to achieve super-exponential speedups in certain cases," says Dr. Angelakis.

Quantum supremacy and limitations

Quantum speed-up is central to the idea of "quantum supremacy," and here is where the next level of tech competition is playing out.

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In 2019, Google's quantum processor solved a computation in less than three and a half minutes versus 10,000 years required for a classical supercomputer. This represents the beginning of a new phase in a global technology race. In 2020, the completion by a photon-computer in China to solve in *200 seconds* a problem that would have a taken a classical super-computer *2.5 billion years*[9] is testimony to the rapid exponential gains that define the race for quantum supremacy.

Despite the massive computational advantages of qubit-driven AI, quantum computing must overcome a host of operational and physical challenges.

Figure 4 – Quantum computing vs. classical computing[10]

Quantum computing	vs.	Classical computing
Calculates with qubits, which can represent 0 and 1 at the same time		Calculates with transistors, which can represent either 0 or 1
Power increases exponentially in proportion to the number of qubits		Power increases in a 1:1 relationship with the number of transistors
Quantum computers have high error rates and need to be kept ultracold		Classical computers have low error rates and can operate at room temperature
Well suited for tasks like optimization problems, data analysis, and simulations		Most everyday processing is best handled by classical computers

First, most quantum processors need to operate in a total vacuum or in a cryogenic environment, in temperatures of around -180 centigrade to absolute zero (-273 Kelvin). This requires a costly and complex staging environment, with specialized requirements regarding infrastructure and equipment. It also requires a large team of physicists, mathematicians, and engineers to manage the esoteric software and algorithms needed to solve ongoing problems. All these resources are in high demand and short supply, a trend that is likely to increase, according to Dr. Angelakis.

Second, compared to classical bit-driven computers, qubit-driven processing currently experiences a high rate of errors. As a countermeasure, huge amounts of auxiliary calculations are required: about 1,000 error-correcting qubits for each calculating cubit.[11] This creates a need for highly specialized algorithms. As a necessary support system, quantum computers rely on classical computers that run micro-processors. The geopolitical and techno-nationalist implications of this last point are significant and will be addressed in Section III of this report.

In contrast, while far less powerful, classical computers have error rates of as low as one in the 10-to-24th power, or just one in a *quadrillion* functions.[12]

There are striking parallels between the early days of quantum computing and the development of the modern electrical based computer, when operating the first oversized machines seemed ridiculously impractical.

Despite these issues, the benefits of quantum computing outweigh the challenges. There are striking parallels between the early days of quantum computing and the development of the modern electrical based computer, when operating the first oversized machines seemed ridiculously impractical.

Built in 1943 in the United Kingdom, the first large mainframe computer filled ten large rooms. Aptly named the Colossus, it had 2,500 vacuum tubes and needed 20,000 punch cards and paper-tape with 5-bit characters to be operated in a continuous loop.

Similarly, America's first "supercomputer" had 17,500 vacuum tubes linked by 500,000 soldered connections. Built in 1945, the ENIAC weighed 30 tons.[13]

In contrast, the tiny microchip operating in a typical hand phone in 2018 held some 6X10^{9th} bits (6 billion bits).[14] In short, a microchip is exponentially more powerful than the Colossus and ENIAC combined.

It should be noted that both Colossus and ENIAC were designed and built with purely techno-nationalist imperatives, in this case, to win the war against Nazi Germany.

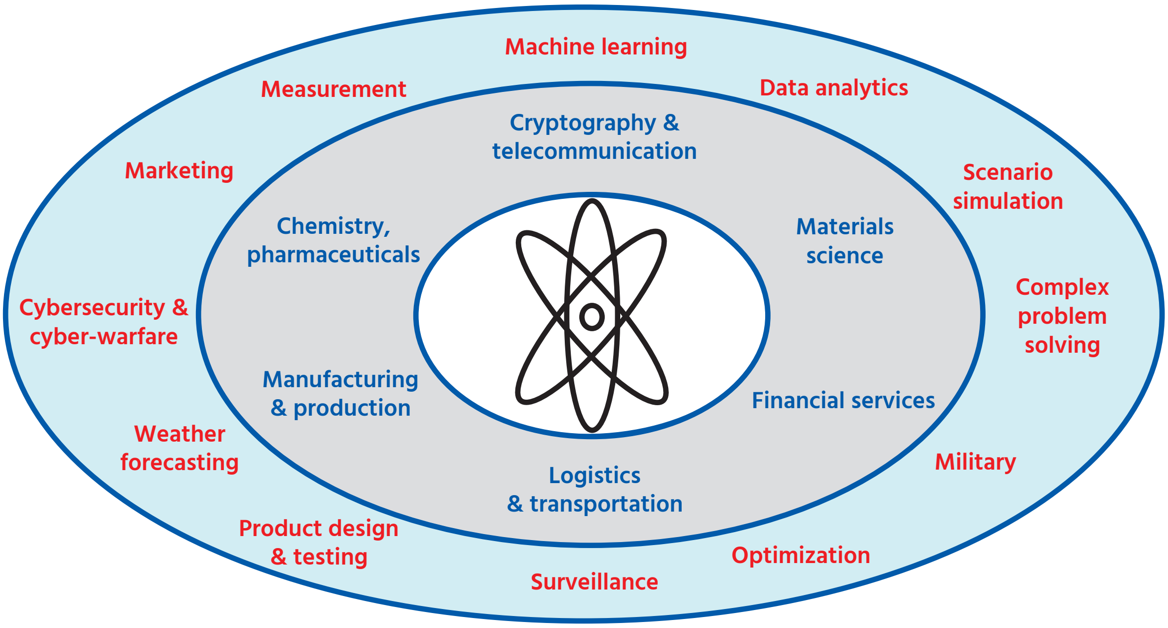
The advent of the microprocessor solved the operating environment and hardware issues of the first vacuum computers. Likewise, a combination of classical digital computing and new advances in quantum computing hardware and operating environments will emerge to create a reliable and eventually affordable symbiosis of quantum and classical computing.

Uses for quantum computing and technologies and why they matter

Like all historic technological innovations, quantum technologies will present both immense possibilities and risks. In general, quantum technologies will fall into three broad categories.

The first is quantum computing. This is used to solve the most complex and advanced computational problems, to process data and information, to perform extensive simulation exercises, and to make complex calculations.

Figure 5 – Potential sectors and practical applications of quantum computing[15]



The second is quantum communication. This allows secure, hack-proof communication networks that can detect any attempts at cyber-intrusions, making it virtually impossible for hackers and spies to gain access to a quantum network.

The third is quantum sensing. Quantum devices are much more sensitive than conventional technology; they can detect motion on a subatomic particle level. The applications are many, from manufacturing to military usage. Imagine a sensor so powerful that a nuclear submarine positioned underwater at a depth of 250 meters could be easily detected from the surface.

Quantum computing, communication, and sensing functions create unprecedented opportunities and risks for state and non-state actors across a range of sectors and applications.

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The first sectors and specialized fields that could be substantially impacted include cryptography, information and communication technology (ICT), chemistry (with direct implications for the pharmaceutical and healthcare sectors), manufacturing and production, material sciences, logistics and transportation, and financial services.

Relevant applications of quantum computing include:

- Simulation and scenario mapping
- Complex problem solving
- Machine learning and AI
- Data sorting and analysis
- Optimization

- Product Design
- Cybersecurity and cyberwarfare
- Marketing
- Specialized forecasting

A techno-nationalist feedback loop connects all these applications to economic and financial actors, political institutions, and the military-industrial complex. In China, for example, national security initiatives are driving Beijing's military-civil fusion.[16] This has resulted in the establishment of the US$10 billion National Laboratory for Quantum Information Sciences in Hefei, Anhui province.[17] In the US, the Defence Advanced Research Project Agency (DARPA) is overseeing increased amounts of funding for R&D initiatives in quantum computing.[18]

Quantum computing is spawning a hybrid ecosystem that combines leading-edge classical computing niches with the brave new world of the qubit. Software and hardware developers are being linked through both private investors and government-led initiatives, while Cloud services have also become integral.

The market value for quantum computing services is significant. It is expected to reach US$780 million in 2025 and grow to US$2.6 billion by 2029.[19]

Practical applications of quantum computing

So far, quantum supremacy has been limited to solving super-complex mathematical problems and equations.

So far, quantum supremacy has been limited to solving super-complex mathematical problems and equations. According to Dr. Angelakis, using quantum computing for practical applications will require thousands of qubits and remains years away.[20]

Although it is impossible to predict when practical applications will become readily available, it is not difficult to see how they will fundamentally reshape the competitive landscape everywhere. Some noteworthy areas are discussed below.

Financial services

Financial institutions have been keenly interested in the practical applications of quantum computing for years. Potential uses include portfolio optimization, high-frequency trading algorithms, fraud detection, and "quantum-proofing" of cyber security systems.

Pharmaceuticals, chemistry, and healthcare

Classical computing's power-multiplying effects became clear during the Covid-19 pandemic. Powerful AI and algorithms were harnessed to sequence the DNA of the virus variants and, in less than a year, produce a series of vaccinations from a sea of data collected and shared throughout the digital global commons.

One of the true marvels of such powerful technology is that it could produce in hours or days life-giving solutions that would take classical computers thousands of years.

With its ability to process billions of calculations per second, how much more can quantum computing bring to solving practical problems and pre-empting a future health crisis? In the race to defeat cancer or devise drugs for other debilitating diseases, the ability of quantum computing to perform simulations involving chemical combinations, specialized applications (including designer drugs for an individual's unique DNA profile), and possible spill-over effects is truly wondrous. One of the true marvels of such powerful technology is that it could produce in hours or days life-giving solutions that would take classical computers thousands of years.

From a global trade perspective, the transformational potential of quantum computing is enormous. For example, millions of patients in Indonesia or Brazil can link with vaccine production in India or the US, and seamlessly align customs pre-clearance procedures with local health and safety laws, data privacy, and other regulations. This saves time and costs, and enhances efficient trade networks.

Trade, logistics and transportation

Leading edge AI and the application of real-time data analysis is already a core competency of the logistics and transportation industry. Exponentially increasing the power of that AI with quantum offers solutions that go beyond just finding the quickest route between two points or matching passengers with drivers.

When calculating the safest and most efficient routes for logistics and passenger modes of transportation, the variables increase exponentially when the number of subjects in motion increases from just one to ten. In urban centres with millions of vehicles, the potential outcome at any given moment is off the charts for any classical computer.

Beyond safety and efficiency, data from connected vehicles in so-called "smart cities" could be used in sustainable, circular economies that reduce carbon emissions and capture kinetic energy, as well as optimise supply and demand scenarios in the sharing economy.

For global trade, quantum computing means instantaneous and real-time calculation of the most efficient shipping routes.

For global trade, quantum computing means instantaneous and real-time calculation of the most efficient shipping routes, from the pick-up of a finished product at a factory loading bay, to its placement in a seafaring container, to its last mile delivery on a bicycle in a remote village on the other side of the planet.

CASE STUDY

Reinventing public key cryptography

Given enough qubits, a quantum processor could figure out a password in a matter of seconds or just a few minutes.

One of the areas that will absorb widespread disruption from quantum computing is cryptography, the essential tool for keeping secrets. Today's encryption methods involve prime number factorization that would take classical computers thousands, even millions of years to solve. Given enough qubits, a quantum processor could figure out a password in a matter of seconds or just a few minutes, by applying Shor's algorithm for prime factorization at extremely high speed.[21]

How long it will take for this moment to arrive is not certain. It could be three to five years, or even ten years, according to Dr. Angelakis. But, "anyone who has secrets that need to be kept for more than 5-10 years better act now," he added.

Therefore, public key cryptography – used for virtually all secure communications on both public and private digital platforms, applications, and devices – could be rendered defenceless to quantum-enabled adversaries. In particular, blockchain, which claims encryption as one of its strong points, could suddenly lose its utility.

Ironically, the best way to protect a password or a network gateway in a quantum world is to employ *quantum countermeasures* in the next generation of public key cryptography. Combined with multi-factor verification data, quantum cryptography will likely become ubiquitous.

Recent state-sponsored cyber offensives against governments and private organizations around the world provide a case study in the possible linkages between cybersecurity, hybrid warfare, and quantum computing.

Recent state-sponsored cyber offensives against governments and private organizations around the world provide a case study in the possible linkages between cybersecurity, hybrid warfare, and quantum computing.

In 2020, the US Department of Homeland Security issued a public statement that named Russia as the instigator of a cyber offensive which gained access to data and communications in at least nine federal agencies, including the Pentagon, the Department of Commerce, and the Department of the Treasury.[22] Additionally, the networks of at least 100 companies, NGOs, and academic institutions had been infiltrated, infected, and pilfered for months by hostile cyber operatives.

In 2021, cyber intruders reportedly attacked some 60,000 known victims around the world, including the European Banking Authority, by exploiting a flaw in Microsoft's business email server software.[23] Hackers obtained access to emails, address books, and calendars.

Orchestrated by leveraging classical technology and aided by the use of conventional "backdoors", spyware, and other hacking techniques, these cyber intrusions netted vast amounts of secret data.

The question is, how much of this hacking will be vetted with the aid of quantum computing, and what advantages will that confer to state actors? There are endless possibilities for authoritarian governments and their clandestine proxies to use sophisticated algorithms to establish linkages between individuals, organizations, ideas, and objectives.

Even the most granular and random bits of data could be harvested for intelligence purposes and tapped to reveal patterns, associations, and relationships. All this stolen data is now waiting to be analysed, as soon as practical quantum technology comes online.

The US-China innovation race and the quantum computing landscape

The race between governments

The US and China are in a race to leverage the practical applications of quantum technology. This involves computing, communications, and sensor technology. The race is on to improve accuracy and to develop real-life applications beyond the solving of mathematical problems.

Both Washington and Beijing have stepped up funding and special initiatives to promote localized quantum R&D, innovation, and strategic partnerships.

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For example, the US Innovation and Competition Act has earmarked support for quantum research from its US$250 billion funding; along with semiconductors, quantum computing is a top priority.[24] Intended to spark collaboration between large organizations, universities, start-ups, and government agencies, the idea is to tap into a deep reservoir of entrepreneurial resources aided by public sector support, incentives, and planning. The endgame: accelerating the growth of innovation ecosystems.

China has also actively supported quantum innovation and its efforts have paid off handsomely. In 2021, the infusion of US$10 billion into the National Laboratory for Quantum Information Sciences in Hefei, Anhui province, has produced major breakthroughs in photonic quantum computing and in quantum key distribution.

Figure 6 – 2021: National quantum initiatives and estimated budgets[25]

US$94m	Australian Research Council Centres of Excellence
US$4.5m	Department of Defence's Next Generation Technologies Fund
US$797m	Industry-academia consortia for quantum technology development
US$287m	National Quantum Strategy
US$79.7m	Quantum Valley Investment Fund
US$10b	QUESS, the Micius sattelite, and other academic programs
US$1.18b	EU's Quantum Technologies Flagship program
US$48.8m	QuantERA program
US$3.1b	Quantum Technologies—From Basic Research to Market
US$797m	
US$1b	National Mission on Quantum Technologies & Applications
US$360m	National Program for Quantum Science and Technology
US$470m	Quantum Technology Innovation Strategy, Quantum Leap Flagship Program
US$740m	Quantum Delta NL
US$1.28b	National Quantum Initiative
US$92.2m	Singapore's Quantum Engineering Program
US$147.5m	Centre for Quantum Technologies
US$37m	Quantum Computing Technology Development Project
US$1b	National Quantum Technologies Programme
US$663m	Quantum Technologies Roadmap
US$1.8b	National Strategy for Quantum Technologies

Other leading quantum research hubs include Japan, the EU (primarily Germany, the UK, and the Netherlands), Taiwan, and South Korea. Singapore and Israel, both small countries, have disproportionally large footprints and could carve out unique positions in the international landscape. In 2021, estimates on the amount invested around the world in quantum technology stand at about US$22 billion. By far, China accounts for the largest percentage of that number.

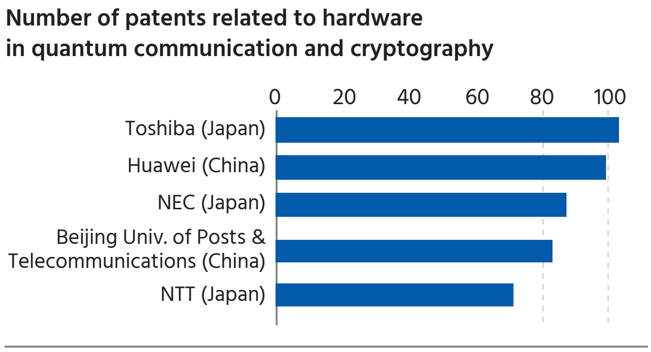
The actual sum of investments in quantum technology may be much higher than what is made public. National security initiatives in the US, China, and elsewhere are typically opaque, though they are likely underway.

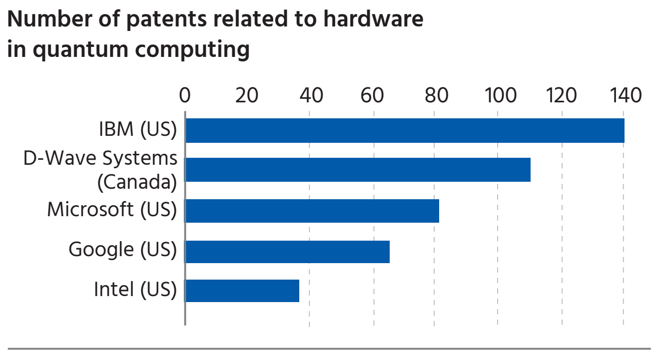
China has filed more quantum technology patents than any other country, including twice as many as the US.

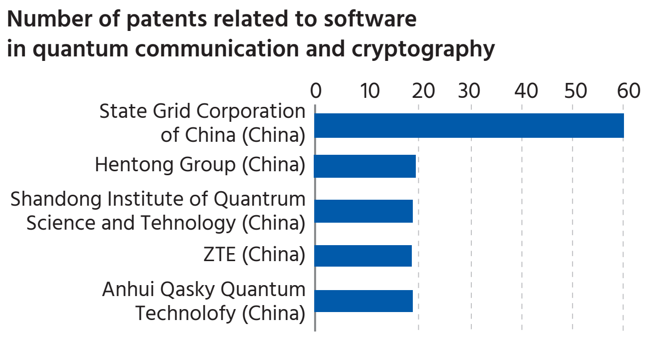
Patent filings as a benchmark

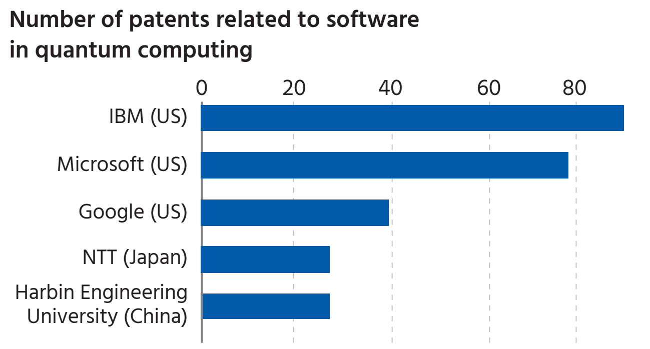
China has filed more quantum technology patents than any other country, including twice as many as the US.[26]

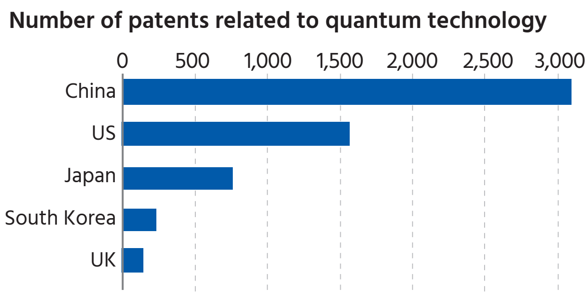
Figure 7 – Which countries lead in which areas of quantum technology[27]











Overall, by country in quantum technology, China has more than 3,000 patents, about twice as many as the US.

While the quantity of patents filed alone is not the most reliable gauge of progress – utility, patent life-range, quality of technology and number of patents filed abroad are also important indicators[28] – China is clearly achieving leading edge innovation in key areas of quantum technology, particularly regarding software for communication and cryptography.

Similarly, the US is leading in patents for both hardware and software in computing, while Japan leads in patents involving hardware for communication and cryptography.

Quantum key distribution (QKD)

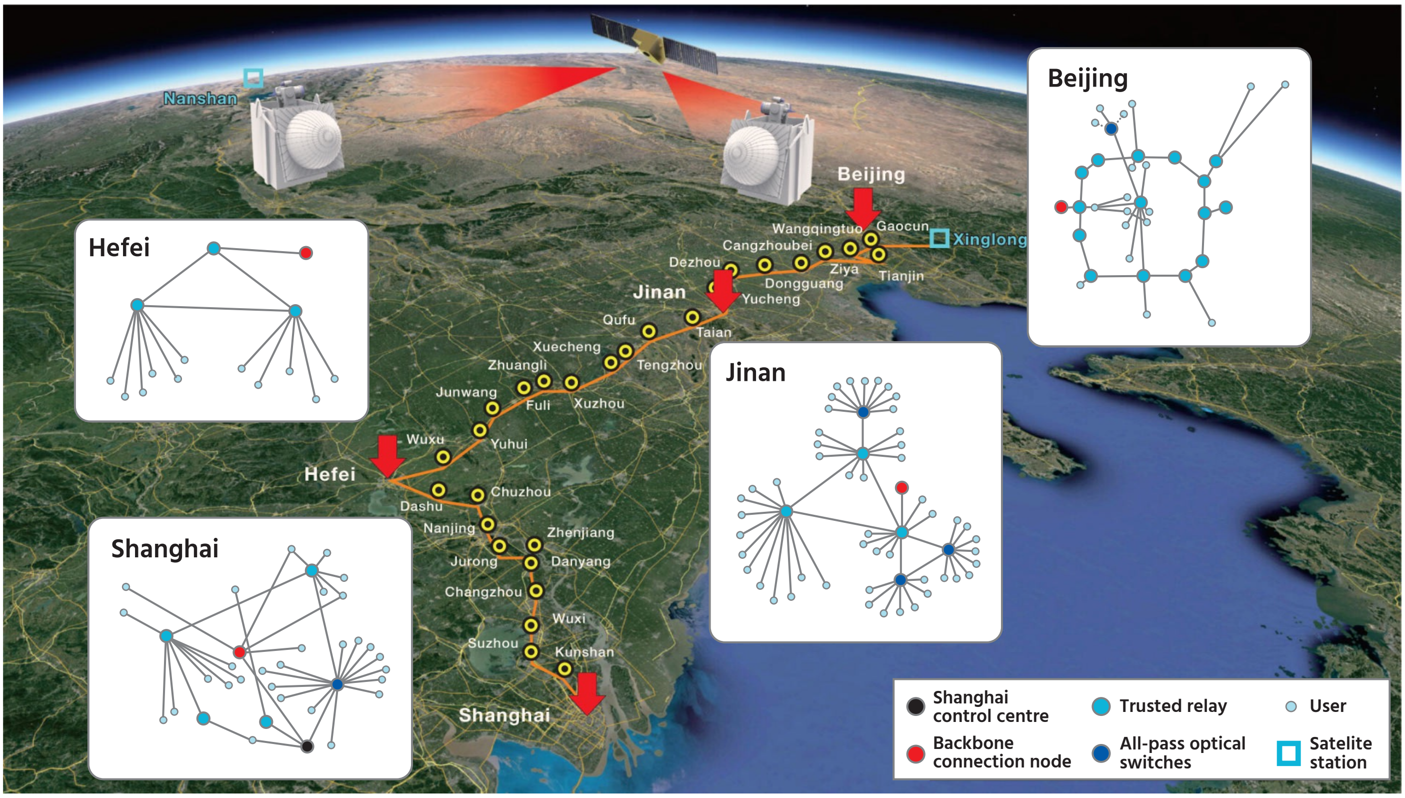
According to a January 2021 study published in Nature, a team of Chinese scientists based at the University of Science and Technology in Hefei developed a breakthrough quantum communication network. Using fibre optic cables and ground-to-satellite links, the network achieved quantum key distribution over 4,600 kilometres amongst a network of connected users.[29]

China's quantum key distribution (QKD) network used bursts of light (photons) bouncing off satellites to relay data-laden qubits in a fully encrypted state. For those who do not have an encryption key, QKD is virtually impossible to covertly access. To do so would rearrange the configuration of 0s and 1s in the qubits and alert the intended sender and recipients to the intrusion. Furthermore, "decoy" transmissions can be mixed into groupings of transmissions.

For those who do not have an encryption key, QKD is virtually impossible to covertly access. To do so would rearrange the configuration of 0s and 1s in the qubits and alert the intended sender and recipients to the intrusion.

Theoretically, the Chinese experiment proved the possibilities of QKD. However, facilitating a large geographically dispersed network requires technology that is currently non-existent.[30]

Figure 8 – An impregnable communications network[31]



Once again, practical applications of quantum technology must wait until necessary advances in hardware and infrastructure occur. But rather than discourage China and others from pursuing QKD, the experiment has only served to inspire more ambitious R&D efforts.

For Beijing, the catalyst took place in 2013. Leaked classified documents detailed how NSA and other US intelligence agencies were infiltrating, monitoring, and exploiting data and communications from China's most secure networks. QKD represents the next great hope for Beijing's safe keeping of its secrets.

China's successful experiment of quantum key distribution showed that it is theoretically possible to create long range communication networks that are virtually impossible for spies and hackers to infiltrate.

The race between companies

Even before the emergence of Washington's aggressive techno-nationalist agenda in 2017, a deep reservoir of tech-entrepreneurism was already sustaining a thriving quantum ecosystem.

The quantum computing landscape is by far most active in the US and Europe, where a multitude of niche players are evolving. Even before the emergence of Washington's aggressive techno-nationalist agenda in 2017, a deep reservoir of tech-entrepreneurism was already sustaining a thriving quantum ecosystem.

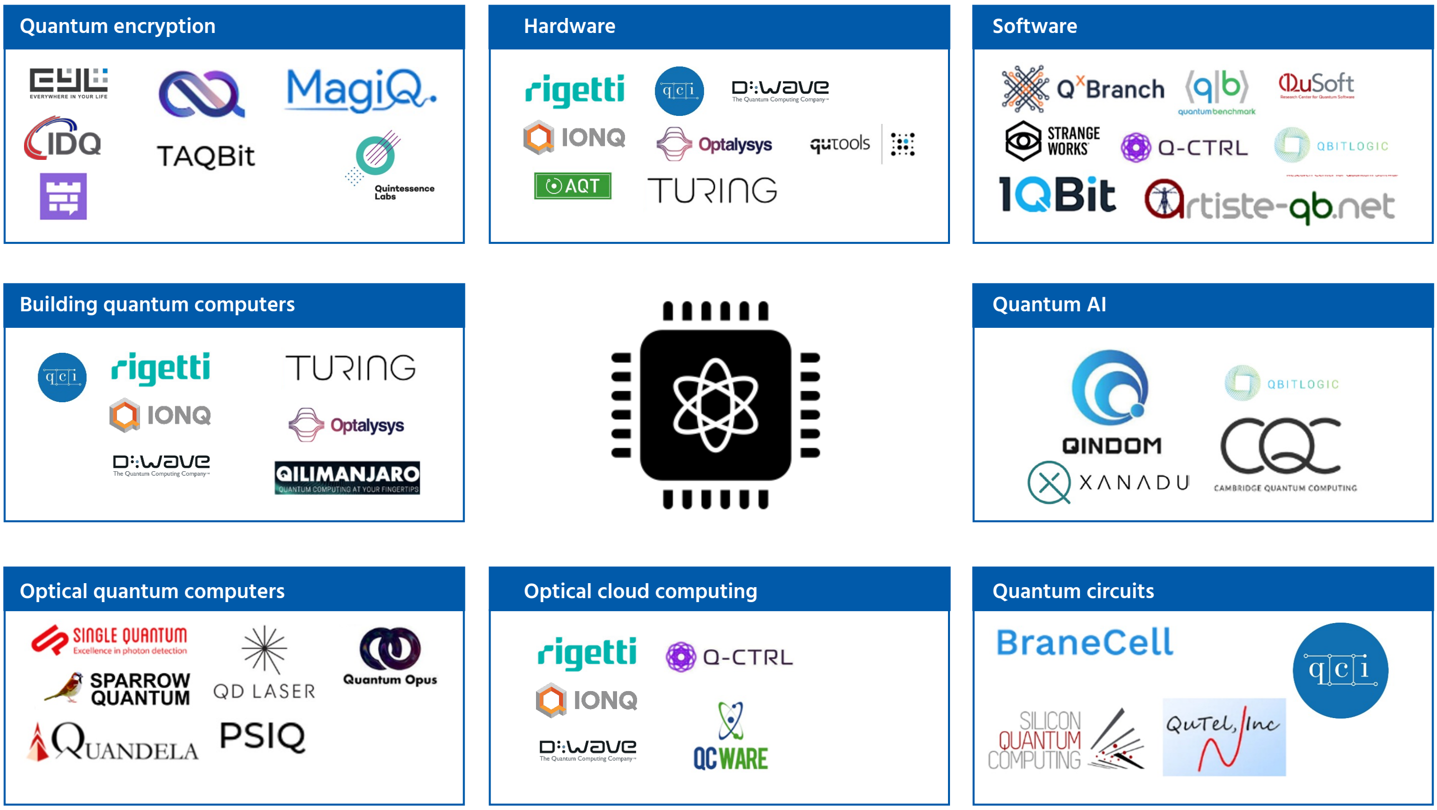
Quantum Daily, a media platform which conducts research, performs analysis, and provides data on market leading companies, has documented a market map that shows US firms dominating the computing space.[32]

Given the need for hyper-specialized hardware, software and other esoteric services, big established companies, and tech start-ups will play an important role in the future race for quantum supremacy. Here, both the US and the EU can harness healthy financial markets, world-leading universities and research organizations, and the military-security-intelligence establishment.

Figure 9 – Western companies are the most advanced in quantum computing[33]

QCs	Superconducting	Trapped ion	Photonics	Neutral atoms	Silicon	Other
Americas	intel qci rigetti D-Wave The Quantum Computing Company *(Quantum Annealing)* Google AI Quantum IBM Q	IONQ Honeywell	PsiQuantum XANADU	QuEra *Cold Atom* atom computing	intel	Microsoft *Electrons on Helium* EeroQ Quantum Hardware *Topological*
Europe, Middle East, Africa	OQC	AQT Universal Quantum				
Asia-Pacific	Alibaba.com				Silicon Quantum Computing	

Figure 10 – The growing quantum computing ecosystem[34]

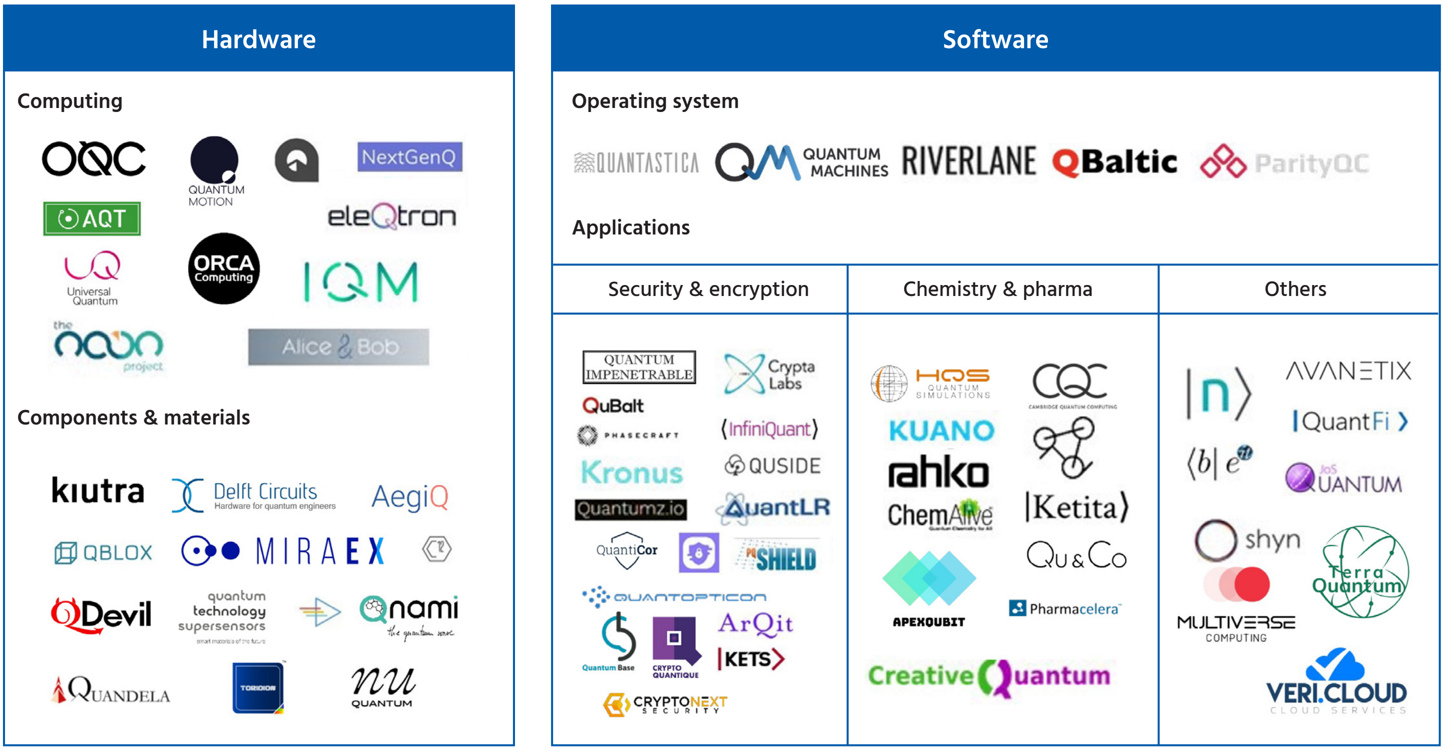


From a government perspective, this confers advantages to Washington and the EU as they leverage robust techno-nationalist feedback loops in their quest to build public-private strategic partnerships.

From a digital trade perspective, the push by the US and Europe toward open-sourced standards, open-banking, and increased trade in services bodes well for the exchange and commercialization of expertise for developing quantum applications.

An open market with healthy measures of risk-taking and hyper-specialization in quantum software and hardware provides opportunities for tech-start-ups throughout global value chains.

Figure 11 – The European quantum computing start-up landscape[35]



Techno-nationalism and the future of quantum computing

From a techno-nationalist perspective, the future of quantum technology will follow the same path as that of the semiconductor. Key stakeholders, including governments, multinational companies, NGOs, and universities will need to adjust to four key trends.

Increased export controls and restrictions on quantum related software, hardware and human capital will require new risk management strategies.

First, increased export controls and restrictions on quantum related software, hardware and human capital will require new risk management strategies. As more companies face the threat of being excluded from global value chains, they will need to look deeply into their partner's supply chains and networks. This means implementing stricter and more vigorous transparency controls, and using IT to keep track of restricted entities, individuals, and technologies.

Second, as a result of increased controls, affected parties will resort to the ring-fencing of strategic ecosystems. This will result in more regionalized and localized trade.

Third, both state and non-state actors will turn to increased "techno-diplomacy." This will include efforts to lobby others to exclude certain parties from participating in R&D communities or to block certain entities from joining public-private partnerships. It will also include the formation of coalitions that seek to espouse similar values and standards regarding the use of quantum science.

New quantum applications are likely to confer disproportionate amounts of power to monopolistic non state actors as well as multiply the power of state actors.

Finally, an intensified techno-nationalist environment will increase the need for new quantum-related ethics, standards, and rules. New quantum applications are likely to confer disproportionate amounts of power to monopolistic non-state actors as well as multiply the power of state actors. This will challenge efforts to curtail the negative aspects of surveillance capitalism and techno-authoritarianism.

Export controls and ring-fencing of strategic ecosystems

Washington and its allies have begun to control access to components, information technology, and human capital as it relates to quantum technologies.[36] The Export Control Reform Act (ECRA), passed in 2018, targets a broad range of "emerging" and "foundational technologies" which include:

- Quantum dilution refrigerators
- Software and AI for quantum cryptography
- Sensor and detector technology
- Semiconductors
- GAAFET technologies[37]
- Microwave technology

Dr. Dimitris Angelakis notes that increased export controls have begun to make cross-border collaboration with Chinese nationals and academic institutions much more difficult. This is compounding the challenges of developing the next generation of quantum thought leaders, as new constraints on student visas come under serious discussion and access to nationally funded research programs by foreign nationals are curtailed.

The esoteric nature of quantum research has created a small circle of experts around the world who have supported each other's research for decades.

Often referred to as the "father of China's quantum program", Pan Jiawen was the lead scientist on China's successful QKD communication experiment in early 2021. Pan Jiawen received his PhD from the University of Vienna, where he was supervised by Professor Anton Zilinger, one of the world's foremost experts on quantum teleportation.

As the Sino-US technology cold war intensifies, academic exchange and collaboration on an international level will face further constraints.

In a previous Hinrich Foundation report on the US-China innovation race, China's "1000 talents program" was examined as a form of techno-nationalism, where China's central planners sought to accelerate knowledge and technology transfer through the world's top scholars and academic institutions. As the Sino-US technology cold war intensifies, academic exchange and collaboration on an international level will face further constraints.

In the US, the Defense Advanced Research Projects Agency (DARPA) and other government agencies have been taking a more active role in overseeing and ring-fencing quantum technology research. DARPA has been actively supervising public private partnerships, such as the Quantum Economic Development Consortium.

It is noteworthy that DARPA, an organization dedicated to national security, has a proactive role in benchmarking programs that seek to influence how quantum technology will be used in medicine and pharmaceuticals, material sciences, and other "practical" applications.[38]

Techno-diplomacy and quantum technology

The US has used its influence to get allies and historical partners to shun China's 5G technology or to cut-off supplies of semiconductors to Chinese tech companies on its restricted entities list.

Washington is employing similar tactics to block access to quantum technology, both on a multilateral and bilateral level. On a multilateral level, the US has proposed to 42 participants in the Wassenaar Arrangement to agree to multilateral licensing restrictions on quantum dilution refrigeration and GAAFET (gate-all-around field-effect transistor) or 3D transistors.[39]

The US has also focused its techno-diplomacy on NATO. As the multilateral defence alliance turns its attention to cyber and hybrid warfare, quantum technology is now a priority.[40]

On a bilateral level, Washington has been actively lobbying the UK, Japan, South Korea, and other nations to decouple their quantum research and development efforts and related value chains from China.

Quantum ethics, standards, and rules

It should raise concern, however, that a handful of Wall Street investment banks or tech giants – Amazon, Google, Facebook – may exploit quantum computing to bolster their already dominant positions.

The applications of one of humankind's most powerful technologies will probably be confined to a small group of governments and well-positioned non-state actors. It should raise concern, however, that a handful of Wall Street investment banks or tech giants – Amazon, Google, Facebook, to name a few – may exploit quantum computing to bolster their already dominant positions.

The expanding threat of surveillance capitalism, coupled with quantum-enabled AI, will complicate efforts to address existing monopolistic and oligopolistic behaviour in the 21st century.

The same concerns apply to state actors. Quantum computing might eventually enable surveillance and population control on a scale unimaginable by Aldous Huxley and George Orwell, two of history's most prophetic writers on authoritarian and dystopian regimes. Therefore, a rules framework on ethical behaviour will be urgently needed.

When the US embarked on the Manhattan Project in the 1940s, the world witnessed the first collision of techno-nationalism and quantum science. The quest to harness the destructive power of the atom ahead of Hitler's Nazi Germany revealed many of the same ethical concerns that have surfaced regarding quantum technology today.

In 1949, a group of 70 scientists on the Manhattan Project signed a petition admonishing President Harry Truman that he would "…bear the responsibility of opening the door to an era of devastation on an unimaginable scale."[41] This document never made it to the President's desk and was only declassified in 1961. But during the Cold War, the scientific community successfully convinced both the US and the Soviet Union to agree to ban nuclear testing, and strive for non-proliferation of nuclear weapons and their eventual disarmament.

Although the next generation of quantum science has yet to be applied in many of the ways previously described, now is a defining movement for the world's leading nations to begin serious discussions about the future of quantum technology. This will have profound consequences not only for trade but for the future state of geopolitics.

Although the next generation of quantum science has yet to be applied in many of the ways previously described, now is a defining movement for the world's leading nations to begin serious discussions about the future of quantum technology.

Quantum science, which harnesses the tiniest of known properties, could eventually deliver humanity's single-largest disruptive technology.

Conclusion

These systemic differences between Washington and Beijing are producing different public private partnerships and market dynamics for large and small companies.

This report has sought to document how quantum technologies, which are still nascent, could be on the verge of ushering in a new age of computing, communication, and sensing technologies.

Quantum technology could have far-reaching geopolitical and trade-related implications that will impact markets, states, and non-state actors.

New quantum-driven applications could produce decisive advantages in competitive landscapes, deciding winners and losers across a wide range of industries, from finance and logistics, to manufacturing, pharmaceuticals and material sciences.

Quantum computing is also expected to upend cryptography and have implications for cybersecurity, data privacy, and the keeping of secrets.

A US-China quantum innovation race has emerged in R&D and the advancement of quantum capabilities. China leads in cryptography and communication-related hardware and software, while the US leads in software and hardware for computational processing. These systemic differences between Washington and Beijing are producing different public private partnerships and market dynamics for large and small companies.

Similar to semiconductors, quantum computing value chains will also face increased export controls and restrictions on the movement of data and human capital. Policies for strategic decoupling and ring-fencing will increase.

As a result, quantum computing is in dire need of rule-frameworks and parameters for the ethical use of new technologies and applications.

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Alex Capri is a research fellow at the Hinrich Foundation and a senior fellow and lecturer in the Business School at the National University of Singapore.

He is the author of *Techno-Nationalism: How it's reshaping trade, geopolitics, and society* (Wiley), due out in 2022.

From 2007-2012, Alex was the Partner and Regional Leader of KPMG's International Trade & Customs Practice in Asia Pacific, based in Hong Kong. Alex has over 20 years of experience in global value chains, business and international trade – both as an academic and a professional consultant.

He advises governments and businesses on matters involving trade and global value chains. Areas of focus include: IT solutions for traceable supply chains, sanctions, export controls, FTAs and trade optimization.

Alex has been a panelist and workshop leader for the World Economic Forum. He writes a column for Forbes Asia, Nikkei Asia and other publications and is a frequent guest on global television and radio networks.

He holds a MSc from the London School of Economics in International Political Economy and a BSc in International Relations from the University of Southern California.

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