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Transformative Quantum Computing: Striving for Greater Heights in Pursuit of Steady Progress

Contents

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Executive Summary

With the advent of the digital age, the amount of data to be processed has become enormous, and complex problems such as material properties, Machine Learning/AI model training, and optimization of social and economic systems require a dramatic innovation in computing technology. However, as the miniaturization technology of semiconductors, which has been explained by Moore's Law, is reaching its limit, the computing power of conventional computing cannot meet the new computing needs required.

Quantum computers, which can accelerate computing time exponentially faster than conventional computers, have attracted attention from governments and academia. Google's announcement in October 2019 that it had achieved "quantum supremacy"*1 in an experiment surprised the world and raised expectations for a new era of innovation in quantum computing in the industry. At the same time, concerns arose about the disruption of existing IT systems and business models. Companies need to take action to capture the potential benefits of quantum computers or avoid the risk of disruption.

Unlike the concept verification at the experimental level, the development of actual quantum computers and business verification that can produce accurate calculations with business value in the real world has not progressed as quickly as expected. Hindered by the slow maturity of technology and the uncertainty of investment returns, there was a possibility that investment decisions by CxOs in the industry regarding quantum computing technology could be delayed.

However, research in this article shows that there is a high level of government and risk money inflow into quantum computing technology, and academic and industrial research and development are advancing rapidly in terms of real quantum computing technology that utilizes physical quantum functions, as well as bridging technologies (digital annealer, a computing technology inspired by quantum phenomena and quantum simulation technologies using conventional computers, etc.). In addition, there have been remarkable advances in support technologies for quantum computer, such as AI and cloud.

We recommend that the industry keeps an eye on the development of quantum computing technology and use case development and corporate adoption trends, acquire knowledge and skills including human resource development, and invest in practical applications through bridging technologies. Such preparation programs, along with the progress of quantum computing technology, will bring the benefits of the coming quantum computing era.

We will guide readers to valuable research, insights, and practical proposals for the industry.

*1 the demonstrable ability of a quantum computer to solve a problem that an ordinary computer could not solve in a realistic amount of time.

1. Overview of Quantum Computing Revolution

In the ever-evolving realm of technology, every so often, a new breakthrough emerges that captures the imagination of both the government and the private sector. Quantum technology is one such marvel. But amongst the various facets of quantum technology, quantum computer stands out as the beacon with the potential to drive the development of new technologies that could revolutionize our world. Industry leaders and innovators stand at the dawn of this new era, eagerly anticipating the myriad of possibilities that quantum computer promises.

Interestingly, the concept of quantum computer isn't as modern as we might assume. In the 1980s, a visionary physicist named Richard Phillips Feynman posed a question that would become foundational for the field. He wondered if computers could simulate the laws of physics, specifically quantum mechanics, and asserted that conventional computers would always fall short. His famous quote, "Nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical," resonates even today. Feynman's early insights laid the groundwork for the development of quantum computers, as he envisioned machines that could operate using the very principles of quantum mechanics that conventional computers struggled to simulate.

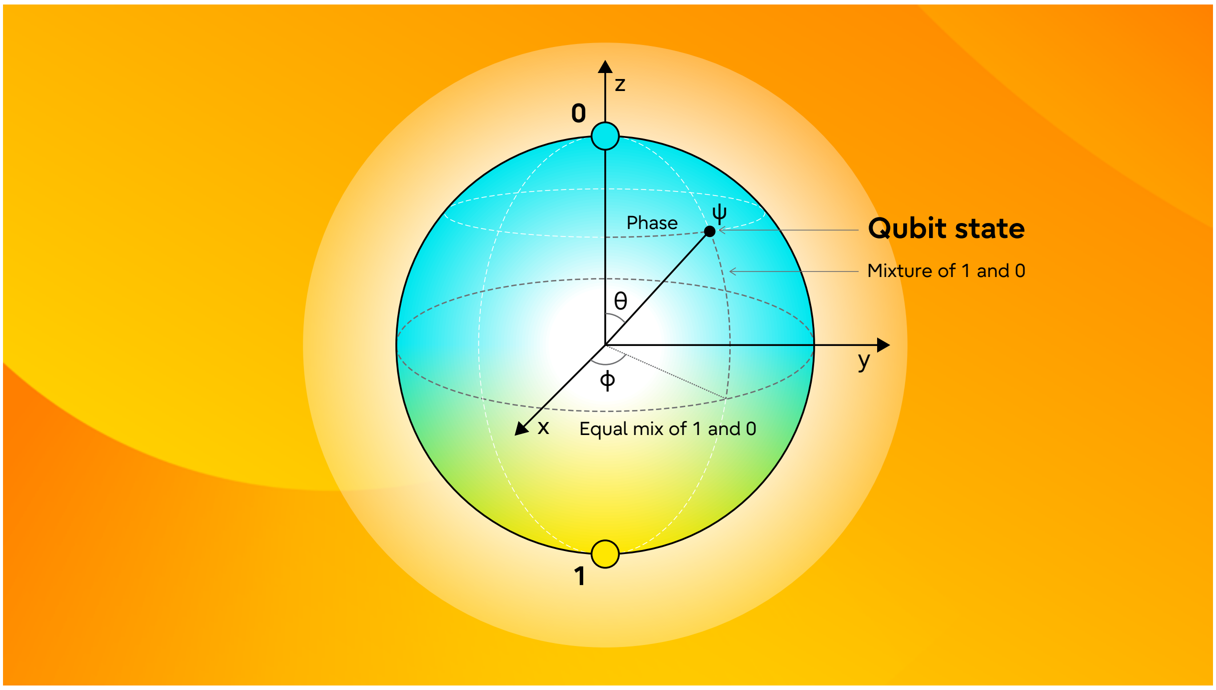
So, what exactly is quantum computer? At its core, quantum computer diverges from conventional computer because instead of the classical bits that represent a 0 or a 1, quantum computer operates with quantum bits, or qubits, that can represent multiple values simultaneously. This is possible thanks to the principles of superposition and entanglement, fundamental tenets of quantum mechanics. Superposition is the phenomenon where a qubit can be in a state of both 0 and 1 at the same time. This is unlike a classical bit, which can only be in one state or the other. Entanglement, on the other hand, is the phenomenon where two or more qubits are linked together in such a way that they share the same fate. This means that if you measure one of the entangled qubits, you will know the state of the other qubit, even if they are separated by a large distance. The ability of qubits to exist in superposition and be entangled is what gives quantum computers their immense power. By exploiting these principles, quantum computers can tackle problems that would be impractical or prohibitively time-consuming for conventional computers.

Quantum computers are in the early stages of development, but there are already very promising applications which conventional computers could not achieve. These applications include drug discovery, material science, financial modeling, cybersecurity, and more. Let us explore this further later on.

At the same time, however, the journey to achieve commercially viable quantum computers is accompanied by numerous challenges. For example, quantum computers need to be scaled up to thousands or even millions of qubits in order to be useful for practical applications. Yet, without stronger error correction strategies, this is a major challenge, and it is not clear how to do it cost-effectively. Quantum computer represents a long-term investment opportunity, which poses challenges in securing widespread interest from investors due to the risks and extended time horizons involved.

It is also worth noting that quantum computer is not a household term yet, and there are a few reasons. Quantum computers are still in their early stages of development and very limited in their capabilities and potential applications. They are also difficult to understand for general public because the principles of quantum mechanics are very different from the principles of classical physics, which is the basis for the computers we use today. As the field of quantum computer continues to develop, it is likely that quantum computers will become more powerful, versatile, and affordable. Once they start to be used for everyday tasks, like ChatGPT, they will become more mainstream.

In the following chapters, we will explore the possibilities and challenges, the economic implications, impact for industries, and use cases. Additionally, we will examine innovations from pioneering vendors, the tangible applications our company is advancing in the quantum domain. Stay with us as we embark on this quantum journey together.



2. Possibilities and Challenges

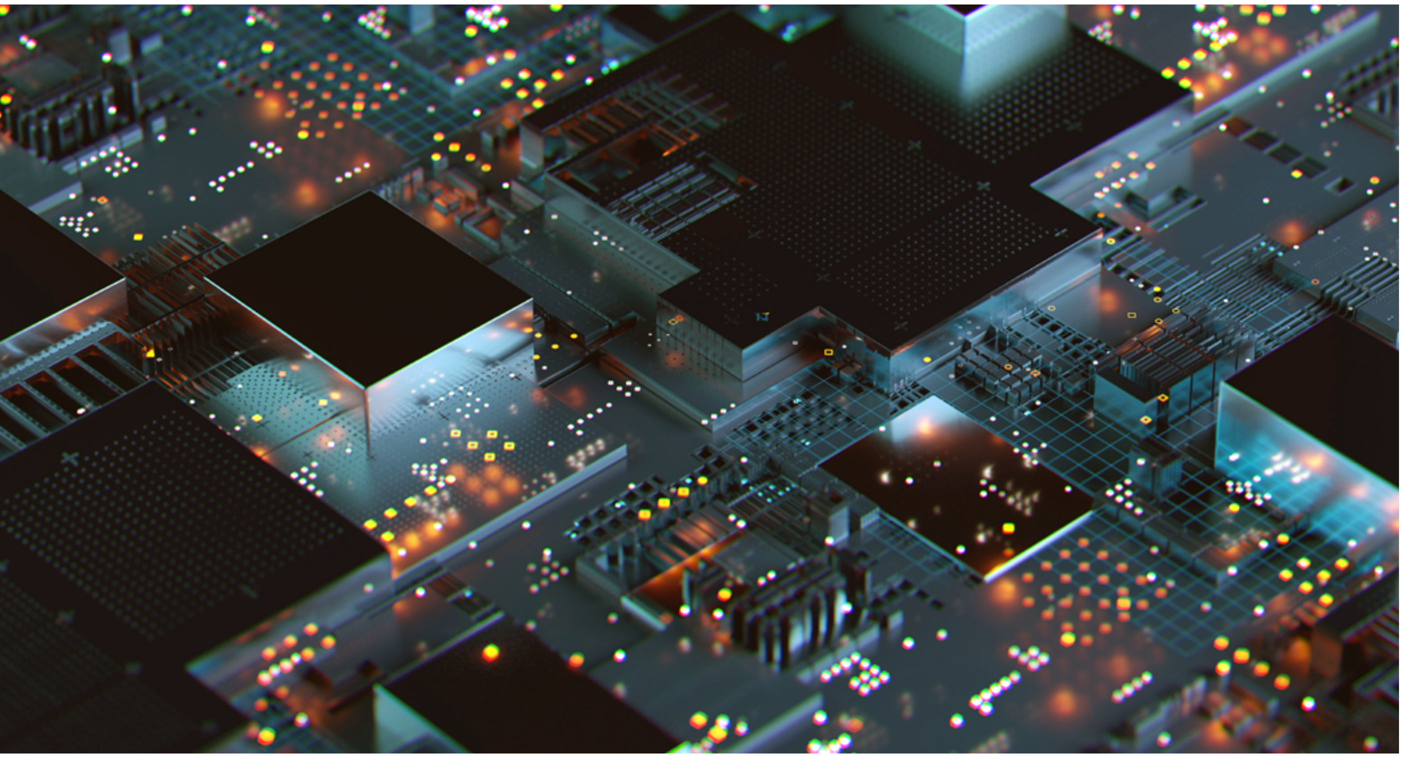
Various Aspects of Quantum Computers

In this section, we will first review the various aspects of quantum computers.

There are several methods for implementing quantum computing hardware (chips), such as superconducting, ion trap, photonic quantum, diamond spin, silicon quantum, and cooled atoms. Some hardware requires an extremely low-temperature environment, like superconducting and ion traps, to maintain their functionality. However, others can function at room temperature depending on the conditions, like photonic quantum, or operate at relatively high temperatures, like diamond spin.

Furthermore, there are various approaches to utilizing qubits related to hardware, mainly focusing on gate models and annealing methods. Quantum computers adopting the gate model are called digital quantum computers, which have the versatility to be applied to all quantum computer use cases. Theoretically, it is possible to measure noise and correct errors. Companies such as IBM, Google, and Fujitsu are actively engaged in development activities, focusing on the potential of versatile quantum computers.

On the other hand, quantum computers adopting the annealing method are called analog quantum computers (quantum annealers). The state of qubit is available, but the quantum entanglement between quantum bits is weak, making it difficult to measure noise and correct errors. However, analog quantum computers have the advantage of being relatively simple to construct compared to digital quantum computers in principle. They can also utilize some of the functions of qubits for specific use cases (mainly quantum optimization). For example, D-Wave is a listed emerging company that has commercialized a representative superconducting quantum annealing computer in 2011.



The Development Process of Gate-based Quantum Computers

Generally, when people think of quantum computers, they envision versatile digital quantum computers, which have three stages of evolution: Component Quantum Computing (CQC), Noisy Intermediate-Scale Quantum Computing (NISQ), and Fault-Tolerant Quantum Computing (FTQC).

While hardware products such as superconducting, photonic and ion traps have entered the NISQ stage, there are few mature hardware products for other methods, and they are at the basic CQC stage. The NISQ stage can demonstrate the superiority of quantum computer and has use cases such as quantum simulation.

The FTQC stage begins when the physical qubits (actual qubits) exceed a certain threshold in terms of quality and quantity, reaching a complete logical qubit (computational logic qubit). However, it is uncertain how many physical qubits are needed to achieve one logical qubit, as this depends on the degree of improvement in hardware performance and error correction techniques. According to a 2019 demonstration paper, it was estimated that 10,000 to 100,000 physical qubits are required for one logical qubit. Fujitsu has developed a new quantum computing architecture in collaboration with Osaka University to accelerate the practical application of quantum computers. With this, if there are 10,000 physical qubits, it is possible to construct a 64-logical-qubit quantum computer, equivalent to about 100,000 times the highest performance of conventional computers. This is considered a significant technological advancement towards FTQC.

Timing for the Realization of Complete FTQC

According to a survey by McKinsey (May 2023) targeting quantum technicians and business executives, 72% of respondents believe that the realization of complete FTQC will occur by 2035, while 28% think it will happen by 2040. In other words, it will take about 10 more years for quantum computers to meet the expectations of the industrial world and become commercially viable. In this sense, it is necessary for governments, academia, and the industrial sector to have economic and commercial incentives that can sustain their efforts for the next 10 years.

Estimating Economic Impact and Promoting Sustainable Development

The quantitative outlook for the economic impact of quantum computer varies depending on the assumptions and estimation models used. According to an estimate based on interviews with industries by McKinsey (April 2023), the economic impact is expected to reach approximately $1.3 trillion by 2035 (with an actual range of $620 billion to $1.3 trillion). However, it is necessary to consider that the economic impact will gradually expand as the number of adopters increases, rather than at a specific point in time.

The impact also varies by sector. Overall, the financial, chemical, life sciences, and automotive industries are expected to experience the greatest impact (in terms of added value), and incentives for joint POCs and adoption with quantum computer vendors are relatively strong.

At the use case level (application), the following four are likely to demonstrate advantages.

1) Optimization

Classical algorithms are advantageous in dividing larger problems into smaller, more digestible problems that quantum algorithms can compute faster. The superiority of quantum computers is demonstrated through the preprocessing of classical computers.
Examples: Portfolio optimization, network optimization, etc.

2) Machine Learning/AI augmentation

Quantum algorithms can achieve at least polynomial speedup in learning specific data classes, particularly shortening the training time of Machine Learning/AI models in the most computationally intensive layers.
Examples: Fraud detection, rapid AI training, etc.

3) Simulation

Quantum computer is expected to have an advantage over conventional computers in accurate simulations (electronic structure or molecular dynamics).
Examples: Pricing methods, material simulation, etc.

4) Quantum Cryptography

Quantum technology can provide new encryption protocols with enhanced security. However, quantum algorithms have the potential to pose a threat to services such as online/mobile communication and bank transfers by breaking current classical encryption protocols.
Example: Shor's algorithm, etc.

Despite the potential technological advantages and economic effects of quantum computer, it will take more than 10 years to realize a practical quantum computing system in terms of technology and economics (cost-performance). Therefore, enablers (driving forces) are needed to stimulate the sustained interest of companies developing and users utilizing the technology. Fortunately, the entry of public funds and risk money is currently maintaining a high level and is expected to continue expanding. For example, IDC's forecast (August 2023) predicts that investment in quantum computers (development, PoC, etc.) will reach $16.4 billion by 2027, with a CAGR (Compound Annual Growth Rate) of 11% over the five years from 2023 to 2027.

From a technological perspective, technology development by leading companies and prominent startups is also becoming more active, with various advancements being reported. For instance, IBM has announced that it achieved 433 physical qubits in 2022 and aims to reach 1,121 qubits by 2023. Fujitsu has successfully developed a high-speed and large-scale 40-qubit quantum simulator using the technology of the supercomputer "Fugaku". Furthermore, following the development of a 64-qubit superconducting quantum computer in collaboration with the RIKEN Institute, Fujitsu has developed a hybrid quantum cloud platform that can be used in conjunction with this superconducting quantum computer and a 40-qubit simulator. This is expected to accelerate the development of quantum chemistry calculations, quantum financial algorithms, and quantum applications, etc. Fujitsu has already entered cooperation processes such as PoC with Fujifilm, Tokyo Electron and Mizuho Financial Group, etc.

In addition, breakthroughs in technology are being observed in terms of quality, such as error correction, maintaining the state of qubits, and extending the computationally feasible time. As previously mentioned, the new quantum computing architecture developed through the collaboration between Fujitsu and Osaka University stands as a compelling example.

Moreover, the economic value brought about by quantum computer is derived from Quantum Speedup, which depends on the complexity of the algorithm, execution time, and problem size. Considering both the technical aspects and cost-performance, it is advisable to think about the optimal adoption strategy for general-purpose quantum computer, analog quantum computer, conventional computer or a mix of these, depending on the use case, task content, or subtasks.

Fujitsu is aiming for a "Computing Workload Broker: CWB" software concept that optimally allocates computing tasks to multiple hardware devices, including quantum computers and HPC, etc., for computational processing optimization. In fact, in the development of the hybrid platform, Fujitsu has also developed hybrid algorithms that automatically combine various algorithms at the upper layers, in addition to the computing hardware layer, to enable optimal calculations. Such achievements are expected to contribute to the acceleration of the realization of a complete CWB.

Constraints and Concerns in the Development of Quantum Computer

On the other hand, there are several concerns and constraints in the progress of quantum computers.

In the short term, there are concerns that the investment stance in the quantum computing field may become conservative due to rising interest rates, being overshadowed by generative AI, or delays in the expected technological breakthroughs.

There are concerns that the use of quantum systems (e.g., using Shor's algorithm) could decipher existing cryptographic systems, disrupting financial order and other areas.

Also, Speedup is challenging, and current algorithms either do not activate the acceleration function or lack sufficient acceleration (secondary acceleration), preventing them from demonstrating superiority over conventional computer.

Furthermore, the immaturity of the value chain, consisting of equipment/components, hardware, software, applications, and services, is expected to persist for a considerable period.

However, these concerns seem to mix macroeconomic and corporate management perspectives with misunderstandings and short-term unfounded worries about quantum computer. For example, Fujitsu used a 39-qubit quantum simulator to run Shor's algorithm to decipher the widely used RSA cryptographic system. As a result, it was estimated that FTQC would need to be executed for Approximately 104 days to successfully decipher RSA, and it was clarified that the possibility of a quantum computing threat to RSA is eliminated in the short term. However, in the long term, it is necessary to prepare for risks, such as the development of quantum cryptographic systems.

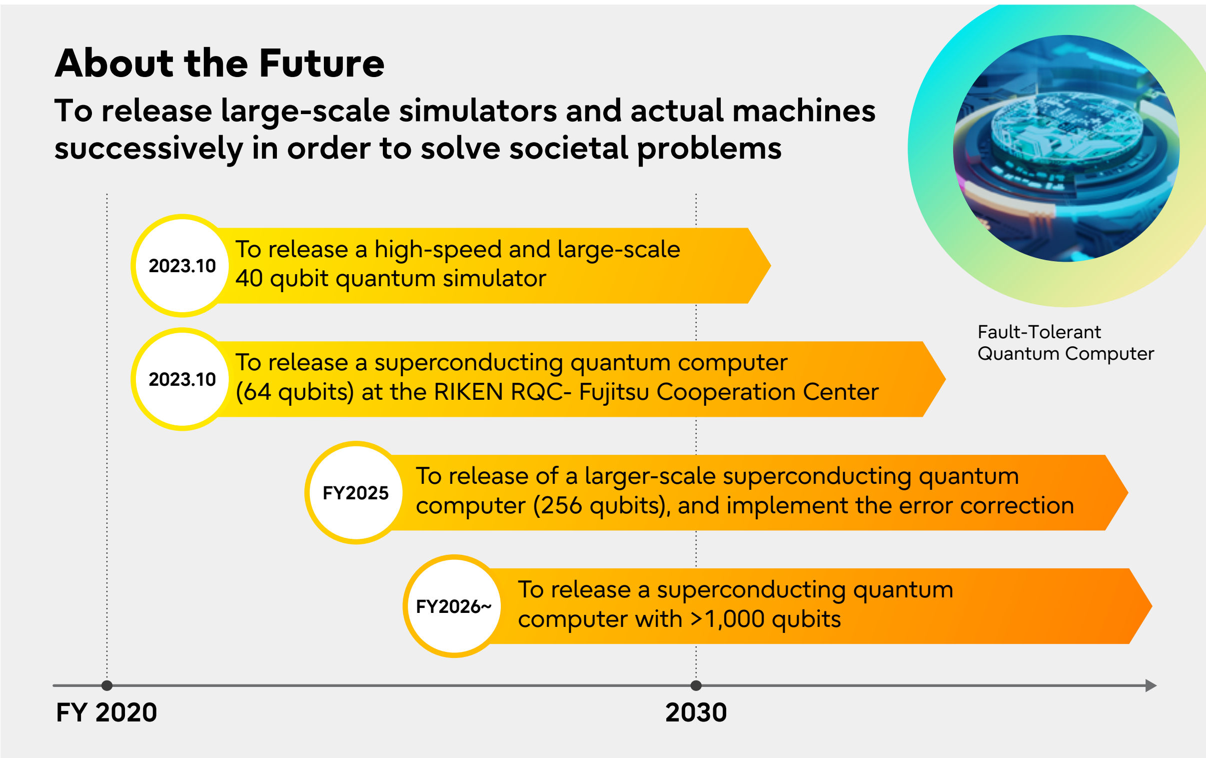
As mentioned earlier, the difficulty of developing quantum algorithms does not require excessive pessimism about conventional computer, and the complementary relationship between quantum computer and conventional computer is being maintained in the long term.

Challenging Problem Solving with High Goals Set by Advanced Vendors

As mentioned earlier, the commercial practicality of quantum computer, which utilizes physical quantum mechanics, lies in a long-term innovation process. However, advanced technology companies and startups such as IBM, Google, ionQ, and D-Wave, which are striving with ambitious goals, are updating their ambitious roadmaps, and accelerating innovation.

As shown in the figure, Fujitsu has set a roadmap to release a superconducting quantum computer with over 1,000 qubits by 2026 and is working to achieve its goals by forming an innovative ecosystem and global network with strategic partners (public research institutions, universities, customer companies, startups, etc.).

We have conducted research and gained insights into innovative quantum computer and related quantum simulations. In the next section, we will present proposals to CxOs of companies.



3. Recommendations

Quantum computer adoption is expected to directly or indirectly benefit nearly every market as a result of the new discovery's and understanding it will bring. However, the organization who stand to benefit most from early quantum adoption are also at the highest risk of competitive disruption driven by early quantum adoption by their competitors.

Recommendation 1 **Early implementation of quantum inspired computing technologies**

Quantum inspired computing is a newly emerging category of computing is giving organizations access to quantum today.

Quantum inspired computing

Quantum inspired computing offers a bridge between conventional and quantum computing by utilizing quantum principles to enhance the capabilities of conventional computing systems, providing improved performance and efficiency in solving complex problems.

Quantum inspired computing offer organization many of the same potential advantages of true quantum computers. This is enabling leading organizations to start their quantum adoption and gain a potentially valuable head start in quantum.

Quantum inspired computing technology such as Quantum emulators and Digital Annealer are expected to play an increasingly important role in providing organizations with access to the benefits of quantum computer and development platforms to develop applications and service that can be quickly migrated to quantum computers when available.

Digital Annealer

One example of quantum inspired computing technology is the Fujitsu Digital Annealer. This popular and flexible Quantum inspired computing technology bridges the gap to true quantum computers and paves the way for much faster, more efficient solving of today's scientific and business challenges. Digital Annealer is designed to solve large-scale combinatorial optimization problems which are unsolvable using today's conventional computers.

Digital Annealers improve the precision and drastically reduces the time required to solve combinatorial optimization problems across many industries, including: making space sustainable (optimizing debris removal), faster molecular similarity search (drug discovery), banking and financial services (low-risk portfolio optimization), distribution (warehouse inventory management) and retail (retail: personalized digital marketing).

Some of the ways Fujitsu customers are using the Fujitsu Digital Annealer:

- Accelerate discovery by POLARISqb: https://youtu.be/mttMA9yrisE
- Improving the management of liquid assets in the finance sector by NatWest: https://www.fujitsu.com/global/digitalannealer/pdf/wp-da-financialsector-ww-en.pdf

You can find out more about Fujitsu Quantum-Inspired technology and Digital Annealer at: https://www.fujitsu.com/uk/trends/quantum-ai/quantum-computing/

Quantum inspired computing adoption

Early adoption of Quantum inspired computing has been particularly strong in the financial and earth science market where competitive advantages can deliver big returns on investment. Prominent financial institutions, such as HSBC, JPMorgan Chase, Goldman Sachs, and Barclays, have already established dedicated teams to pinpoint opportunities for quantum and to drive quantum development and adoption.

Organizations who choose to take advantage of quantum inspired computing such as using quantum simulators, to develop software and solutions will be able to migrate these directly to new quantum hardware. This will put them in the strongest position to take early competitive advantage of the extra power and performance quantum hardware will provide.

The risk of market leaders gaining increased competitive advantages from early quantum adoption is also driving other competitors in the market to accelerate their own quantum adoption to avoid being left at a competitive disadvantage and to regain competitive parity.

Recommendation 2 Preparatory program for the arrival of the quantum computing era

The industry needs to monitor the progress of quantum computing technology, as well as the development of use cases and corporate adoption trends. It is important to acquire knowledge and skills, including the development of human resources.

Highly prioritized industries and use cases are listed in the table.

1. Pharmaceuticals and Biotechnology	6. Modeling and Simulation
2. Finance and Investment	7. Aerospace and Defense
3. Cryptography and Cybersecurity	8. Telecommunications
4. Artificial Intelligence and Machine Learning	9. Transportation
5. Supply Chain and Logistics	10. Materials Science and Chemistry

Quantum computer hardware adoption

The adoption of practical quantum computers once available is expected to be rapid driven by the competitive advantages it will provide to adaptors. Industries such as financial services, chemical sciences, life sciences (pharmaceuticals), automotive, aerospace, defense, semiconductor design, and advanced materials research are expected to be particularly keen on adopting this technology.

However, it will take time for organizations who have not previously taken advantage of quantum inspired computing to develop the quantum software and services they need. The lead time this will require will potentially leave them at a competitive disadvantage against early adopters who have taken advantage of quantum inspired technology.

People

To harness the potential of quantum technology, requires a specialist team with specialized quantum skills. Today these skills are unlikely to exist in most organizations, so this leaves organizations with two options to recruit the specialized consulting, development, deployment and support skills they need or to partner with an organization who can provide all the skills and support they needed to support quantum adoption.

Specialized quantum staff are already in high demand today with 20%-25% of available specialized quantum roles remaining unfilled. Demand is increasing and expected to jump significantly once quantum computer hardware becomes available and mainstream adoption starts. This will make it increasingly difficult and expensive to attract and retain specialized quantum talent.

This may also make it more attractive for organizations to work with an outsource partner to provide the specialized quantum talent needed to support their quantum projects and systems.

Recommendation 3 **Take a high-level perspective and proceed in order with "Check and Go"**

Where to start

The very first generation of practical quantum computers are expected to be far more expensive and challenging to own and operate than today's binary computers. Quantum computers need to operate at as close to absolute zero (-273.15 °C) as possible. As a result, first generation quantum computer systems will not be something organizations can simply, buy, unbox and plug into a rack in their server room and use.

The very first adopters of quantum computer hardware are expected to be governments, academic institutions, and major corporations. It is also expected that many organizations will choose to partner with a provider who can provide quantum computer as a service. In the same way supercomputer as a service is provided today. This may be a far more convenient and cost-effective approach for many organizations.

How can quantum benefit organizations?

Quantum computers will not directly replace today's conventional computers, and organizations will continue to operate conventional computer systems for day to day computing the foreseeable future. However, quantum systems will increasingly be used by organizations who have tasks that can benefit from the radically faster computational power of quantum.

Conclusion

1. Identify where quantum could enhance your organization.
2. Consider if your organization is at risk of disruption driven by competitor's quantum adoption.
3. Consider using quantum inspired computing today to start benefiting from quantum.
4. Find the right specialist partner to help advise and guide you in your quantum adoption.
5. Avoid been driven to adopt quantum to regain competitive parity with your competitors, the lead time for quantum development will make it hard and expensive to catch up and restore competitive parity.

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- Transforming Supply Chains to Be More Productive, Resilient, and Sustainable (2023)
- Transformative Enterprise 5G: To Become an Attractive Enabler for DX (2023)
- The Composable Enterprise Emerging in the VUCA Era: From Concept to Practice (2023)
- Digital Transformation in Manufacturing: Top Challenges CxOs Face and Proven Solutions (2022)
- Transformative 5G in the IoT Era: how to realize its potential, from verification to implementation (2021)
- Achieving Efficiency and Resilience Across Global Supply Chains with Digital Technology (2020)

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