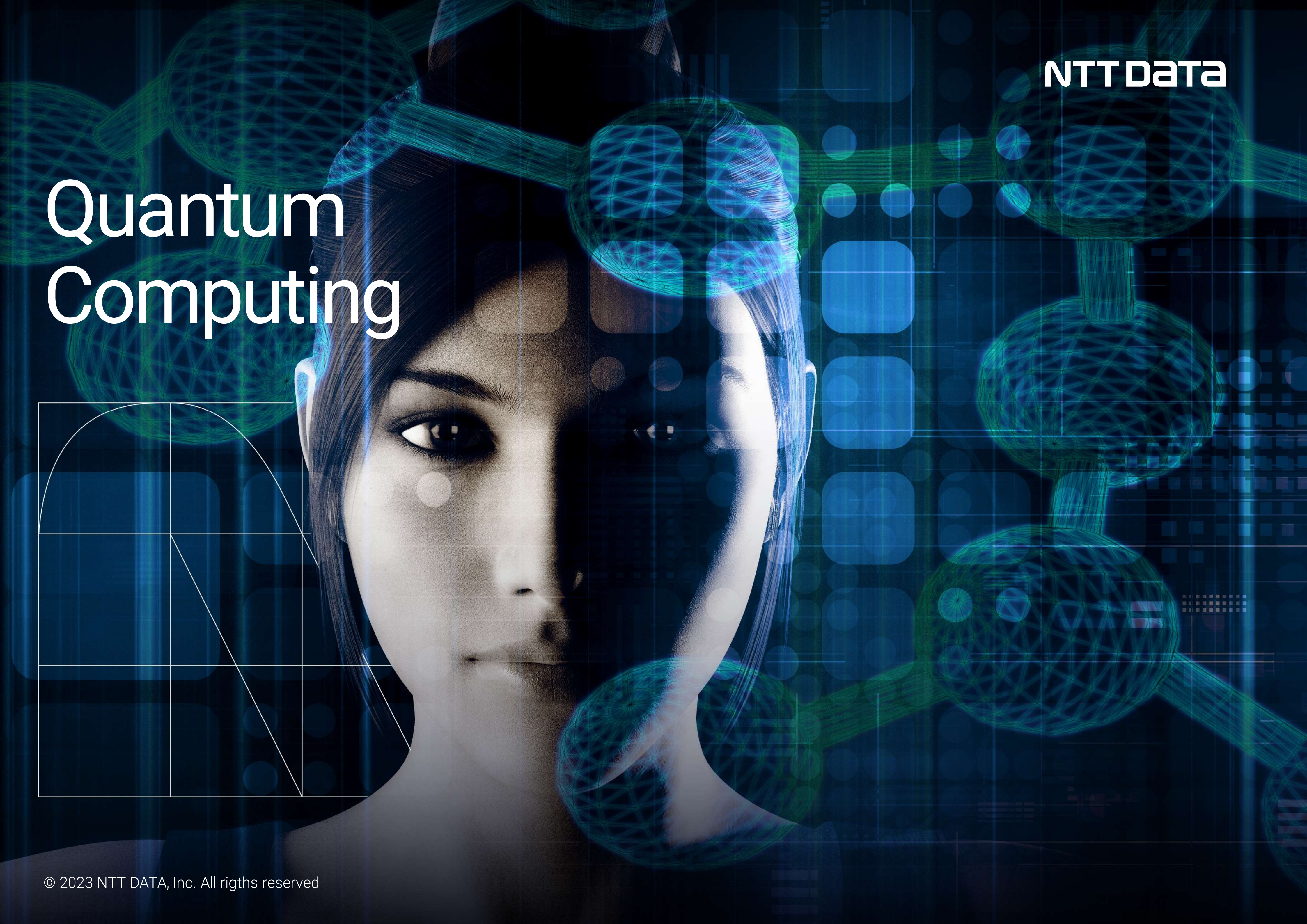
Quantum Computing



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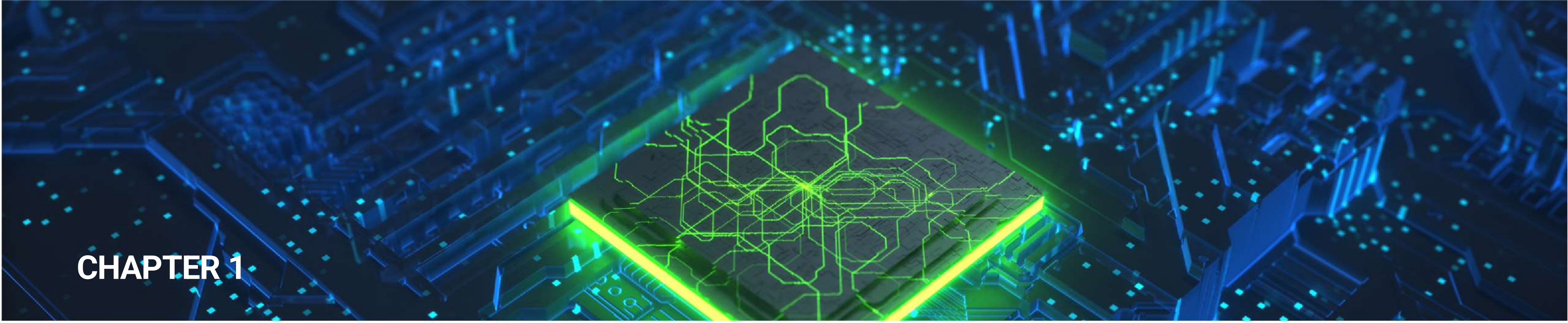


The Case for Quantum Computing

MEANING AND RELEVANCE

Quantum Mechanics has been an irresistible focus for research since Max Planck's seminal paper on the problem of Black Body Radiation in 1900, and the (sometimes robust) discussions with Einstein and others in subsequent years. The simple proposition: that bodies at a sub-atomic- or Quantum-level operate to different rules compared with those existing at macro level, has led to debate, controversy and endless speculation about potential applications.

Not many people could give a short biography of Erwin Schrödinger, but a lot of people have heard of Schrödinger's Cat and, of course, quantum phenomena are now a staple of science fiction, ranging from the Marvel Comic Universe to the popularization of particle entanglement in Liu Cizin's "Three Body Problem". The latter series of books, with readership in the tens of millions, may not have contributed much to true scientific understanding, but it has led to a lot of people spending time wondering about quantum phenomena.

So, what relevance does it have to us, in business terms, today and into the near future? To understand that let's consider what quantum computing is and has the potential to become.

LIMITATIONS OF CLASSICAL MECHANICS

All present-day computers are what is known as "Von Neumann" devices, named after the Hungarian-American polymath John von Neumann. They operate to the principles of classical mechanics, and that imposes certain limitations on them. For example, classical mechanics states that the loss of information gives off heat.

That explains why cooling systems become more essential for any computing device as the amount of data being processed increases. It also means that power usage increases until a (as yet) theoretical point is reached where it is impossible to input the level of power required to process a certain level of calculations. Classical computers have only remained viable over the past few decades because of Moore's law, which states that the number of transistors on a dense Integrated Circuit doubles every two years.

This is an observation, rather than a law of physics and, just like the balance between power, heat and processing, it has a natural limit. In other words, there is a point where computers based on classical mechanics cannot be made to operate more quickly and efficiently anymore. We cannot say how close we are to this limit, but it is gradually becoming visible.

Is this a problem? Potentially the answer is yes.

THE CHALLENGE OF DATA

As conventional, classical computing reaches its limits, we are faced with a growing dilemma, not in terms of theoretical physics but right here, in the real world and real economy. The dilemma is focused on data.

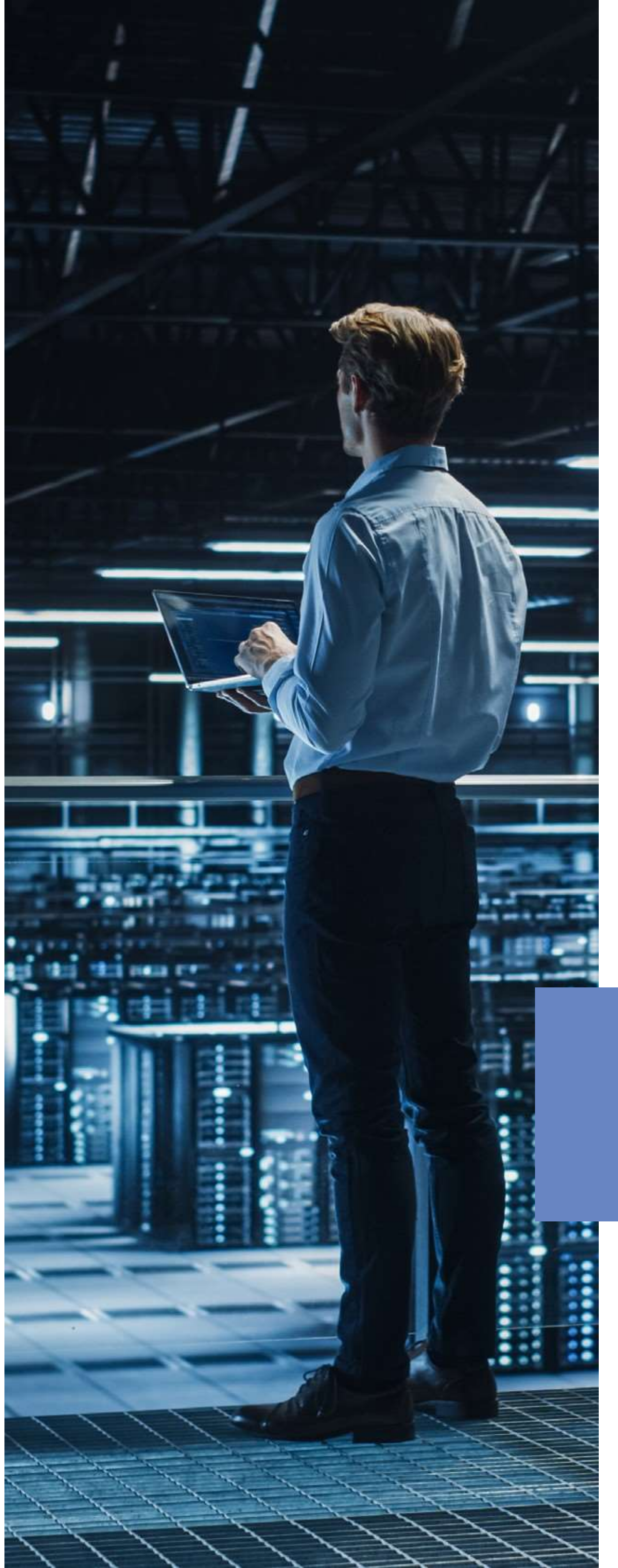
Every sector in the modern economy depends on data flows, processing and rapid analytics, all in quantities that grow exponentially..

Does that matter? Well, yes it does. Given the natural limits of classical mechanics, there will come a time when our assumption that real time data analytics, supported by an increasing use of AI, will always be at the heart of modern business applications looks somewhat optimistic.

This is especially important for solutions that relate to complexity in all its forms and for Combinatorial Optimization. These are problems that include a vast number of candidate solutions, with relational conditions (how each component relates to all the others) that cannot be successfully addressed by conventional means.

In simple terms, that means finding patterns within vast and continuously changing datasets. To deliver the insights we require, conventional computers have to ask a vast number of simple questions of the data over and over again, at very high speed. Quantum computers work differently, as we shall see.

As the world faces growing challenges related to complexity (smart city solutions, supply chains, logistical planning as traffic conditions change, medical diagnostics and many, many more...) so the need to move on from classical computing methods becomes more urgent. At some as yet unspecified point in the fairly near future, only novel forms of computing will be able to deal with these challenges.



USING THE QUANTUM PARADOX

The paradox of quantum mechanics is that specific components (sub-atomic particles) can hold different positions and states at the same time through entanglement and super-position.

Particle entanglement proposes that, once "entangled", particles can remain in association with each other even if one is physically at an enormous distance from the other (the other side of the galaxy, for example). Super-position means that the basic unit of quantum computing (known as the qubit) can hold both 0 and 1 states simultaneously.

This means that, instead of carrying out many different computations, making positive or negative judgements one after the other, a quantum computer can make these many different calculations all at the same time. As the complexity of the calculations required grows, so the business advantage delivered by quantum computing also grows. As we reach the point of requiring responses to problems of extreme complexity, we will reach the point where only this approach can deliver the outcomes we require.

This is sometimes known as "Quantum Transcendence", the ability of quantum computers to solve problems that cannot be solved in a useful or reasonable time by classical computers.

We are not at this point yet, but we need to be ready. That's why NTT DATA is focusing on the subject strongly and for the long term.

In the rest of this paper, we set out some of the insights and practical next steps that will take us into a new world of everyday quantum computing by 2030.

CHAPTER 2

Current Status, Emerging Developments

MAJOR CATEGORIES

Quantum computing is a simplistic description for a complex set of existing and potential architectures. The different options may prove to be especially compatible with different forms of problem and industry. For example:

- Quantum Gating computers have an affinity with data exploration, and this makes them suitable for the finance industry and some forms of advanced research into (for example) chemistry and pharmaceuticals.
- Quantum Annealing and Ising machines (which use a similar approach to simulated annealing) are highly suitable for rapid and high-volume computation, such as combinatorial optimization, applicable to logistics and supply chain problems.

Quantum Gating is the method which is expecting to have a huge impact on a future market while Quantum Annealing has been tested for practical use. Quantum Gating can itself be sub-divided into different technology build structures, all of which have specific operational characteristics and error rates. These include Superconducting, Trapped Ion, Semiconducting quantum dots and Optical systems: all covered by a separate publication that investigates the science of quantum computing in much greater depth than is appropriate in this paper.

Research is being carried out into all these and other forms of quantum computing machines, with some of the world's leading IT corporations, with specialized research institutes and other academic bodies also involved.

The greatest concerns relating to all existing forms of device is the level of errors that need to be reviewed and corrected before any quantum computer can deliver the desired outcomes. Now, trade-offs in different performance parameters are inevitable.

Current levels of development work, therefore, are focused on areas where performance issues impact on outcomes and are designed to deliver practical solutions that unlock the full potential of this vital new technology, without compromise. In the meantime, attention is increasingly focused on an existing, hybrid approach that is ready to use today.

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NOISY INTERMEDIATE-SCALE QUANTUM (NISQ)

Developed at the California Institute of Technology as part of the AWS quantum research activity, NISQ is defined as "noisy" because error correction is not implemented, and computational errors ("noise") are therefore included in outputs. The advantage of NISQ is that it exists today and can be used as part of a hybrid approach that includes some use of classical computing.

Running quantum routines with no error correction means that outputs cannot be completely accurate but will deliver suitable responses within a known spread of probabilities. As efficient error correction techniques are not available, NISQ provides the fastest way to achieve at least some of the benefits associated with Quantum Computing. It is possible to create combined Quantum and Classical algorithms that limit both the scale of the datasets analyzed and the likely error levels.

As NISQ comfortably exceeds the potential speed of classical computing, even at the comparatively low level of 100 Qubits, the result is an advance on currently achievable analytical capability, via a solution that can be developed, built and put to work right now. NTT DATA believes that, while work on error correction solutions continues, this is one of the leading candidates to employ this new technique today.

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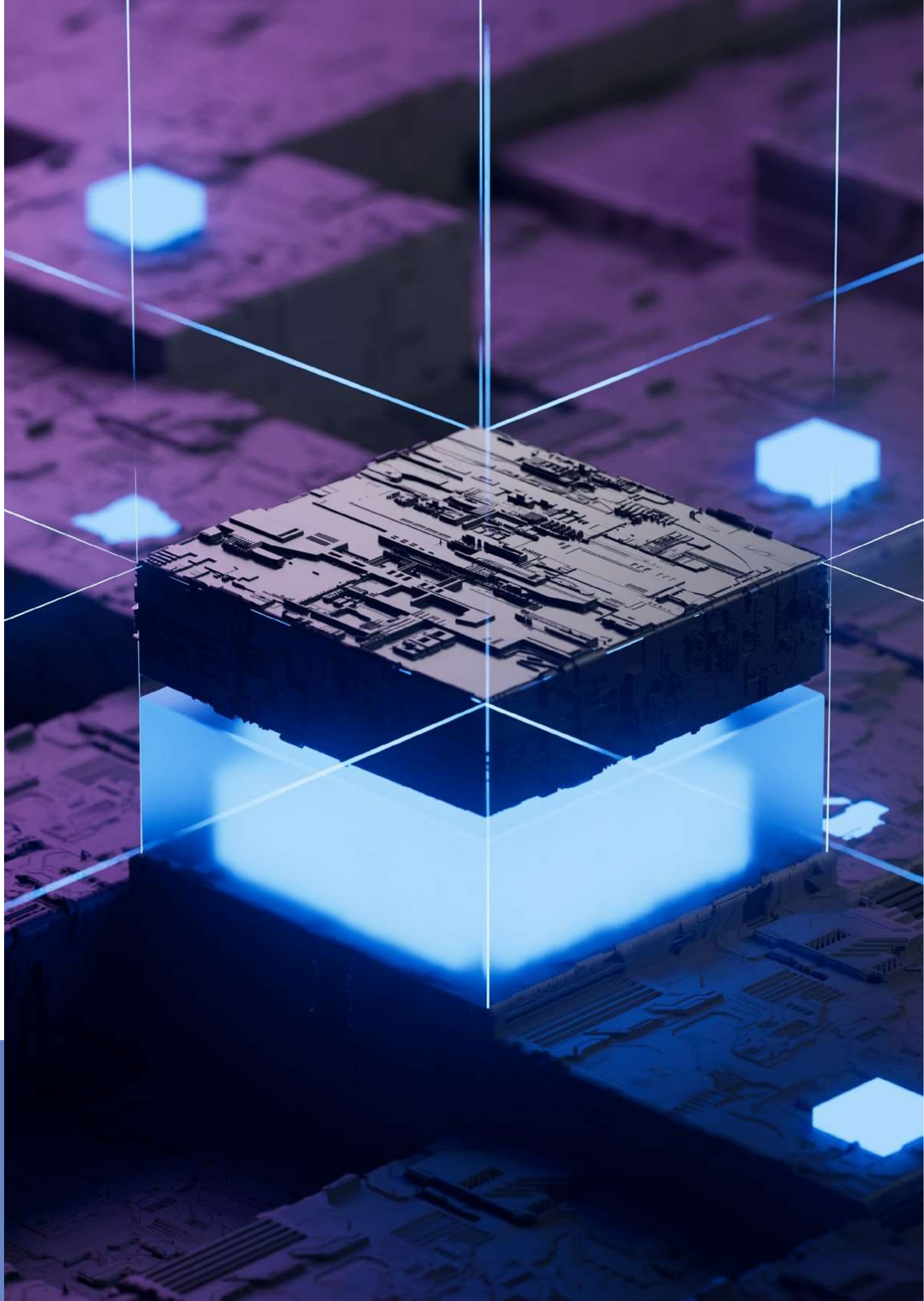


APPLICATIONS TODAY

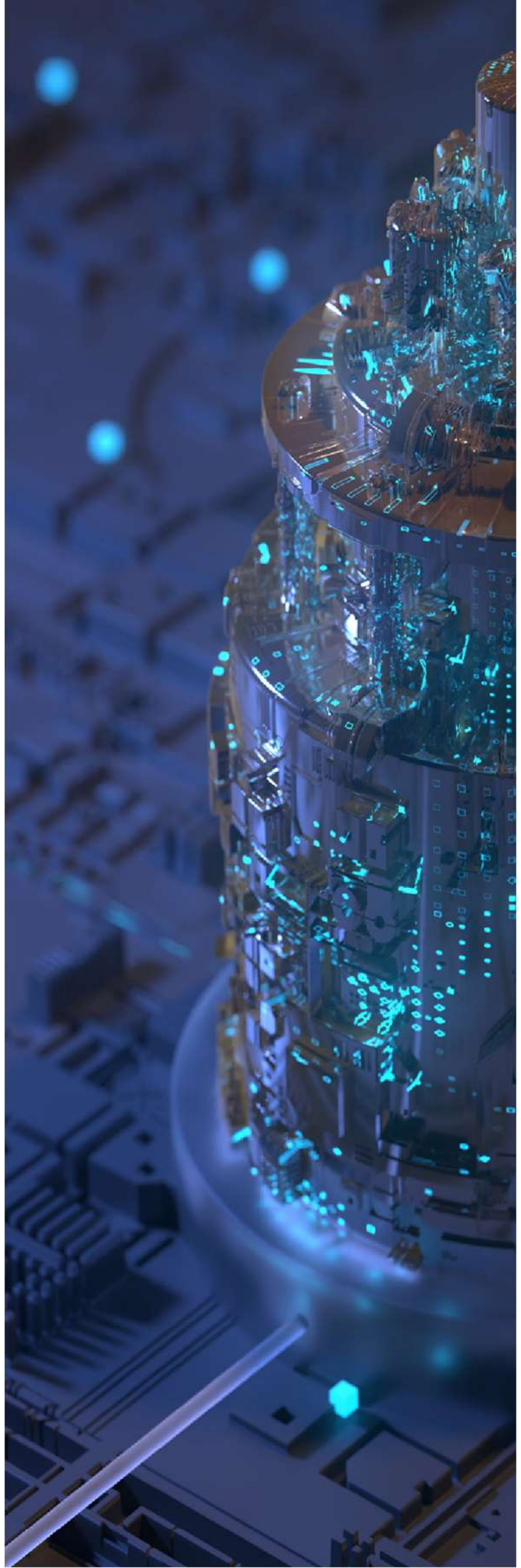
Different forms of machine and technique are suited to different types of problem or task. By analyzing the main computational tasks encountered in different industries, we can start to build a picture of use cases.

In each case the primary requirements will be for cases that involve very large datasets, the need to identify optimal paths or patterns, and the existence of many different potential solutions. To illustrate the ways in which exponential increases in computing power are needed as the number of factors grows, we can look at the well-known traveling salesman problem.

To identify the most efficient path between different visits (or drop-off points) we see that, with 4 possible bases, the number of options is 24. Increasing the number of bases significantly, however, leads to exponential growth in possible solutions. If there are 26 bases (or stops) the potential number of options rises to 403291461126605635584000000.

Conventional methods can be used to optimize most logistics patterns, at least to the point where a reasonable solution is delivered. Once the underlying data becomes even more complex, however, classical computing cannot find the right answer. In Chemical research, for example, optimizing patterns within quantum chemistry requires quantum computing. Classical mechanics cannot deliver a usable solution.

Other, similar examples exist across the global economy. As we collectively move to enhance performance against a wider range of parameters (now including circular economy and environmental / natural capital measurements, as well as classic business measures, so the levels of complexity increase and the need for faster computation becomes more urgent.



They are likely to include:

- **Financial Services.** Measure yield curves, optimize portfolios, thereby selecting the best possible asset distribution out of all portfolios and items under consideration, leading to highest return on investment.
- **Smart cities and transportation networks.** Managing a large number of variables that impact on traffic management in the context of crowded transport networks and international freight movements.
- **Manufacturing.** Managing multiple assets to optimize lifecycles, reduce downtime, enhance productivity and deliver maximum operational efficiency and minimum waste, pollution and emissions.
- **Logistics and supply chains.** Identifying all stops, participants and variables in a complex global chain, ensuring product pedigree, highest levels of security and efficient management of traffic flows.
- **Life Sciences and Chemistry.** Enabling pharmaceutical companies to identify potential winning new molecules as fast as possible, making the entire process of drug discovery, refinement and increasingly, individualization more efficient. Supporting the development of quantum chemistry applications.
- **Connectivity and smart machines.** Enabling networks (telecommunications, intelligent cloud, power grids…) to be structured for optimal performance, while helping to develop enhanced machine learning options and evolution of controlled AI.

Many other options are being defined across the industry, but these are known, urgent and can only be delivered through at a least a hybrid quantum / classical approach, as levels of complexity encountered today have already extended past pure classical mechanics.

ENVIRONMENTAL PERFORMANCE

There cannot be a more urgent task confronting scientists and technologists today than that of addressing the climate crisis. We have already seen that use of quantum mechanics as the basis for future computing has the potential to by-pass some of the most worrying aspects of classical mechanics: use of heat and energy.

Landauer's principle states that, whenever information is lost (which happens during a classical computing task), heat must always be generated. This principle has been observed in practice continuously over the past almost 80 years, since the very first computing devices were put to work.

It therefore follows that, as the number of computations increases, so the amount of heat created grows. That means extra power is needed as an input (to run the machines doing the calculations) and for environmental management (to cool the machines that would otherwise overheat).

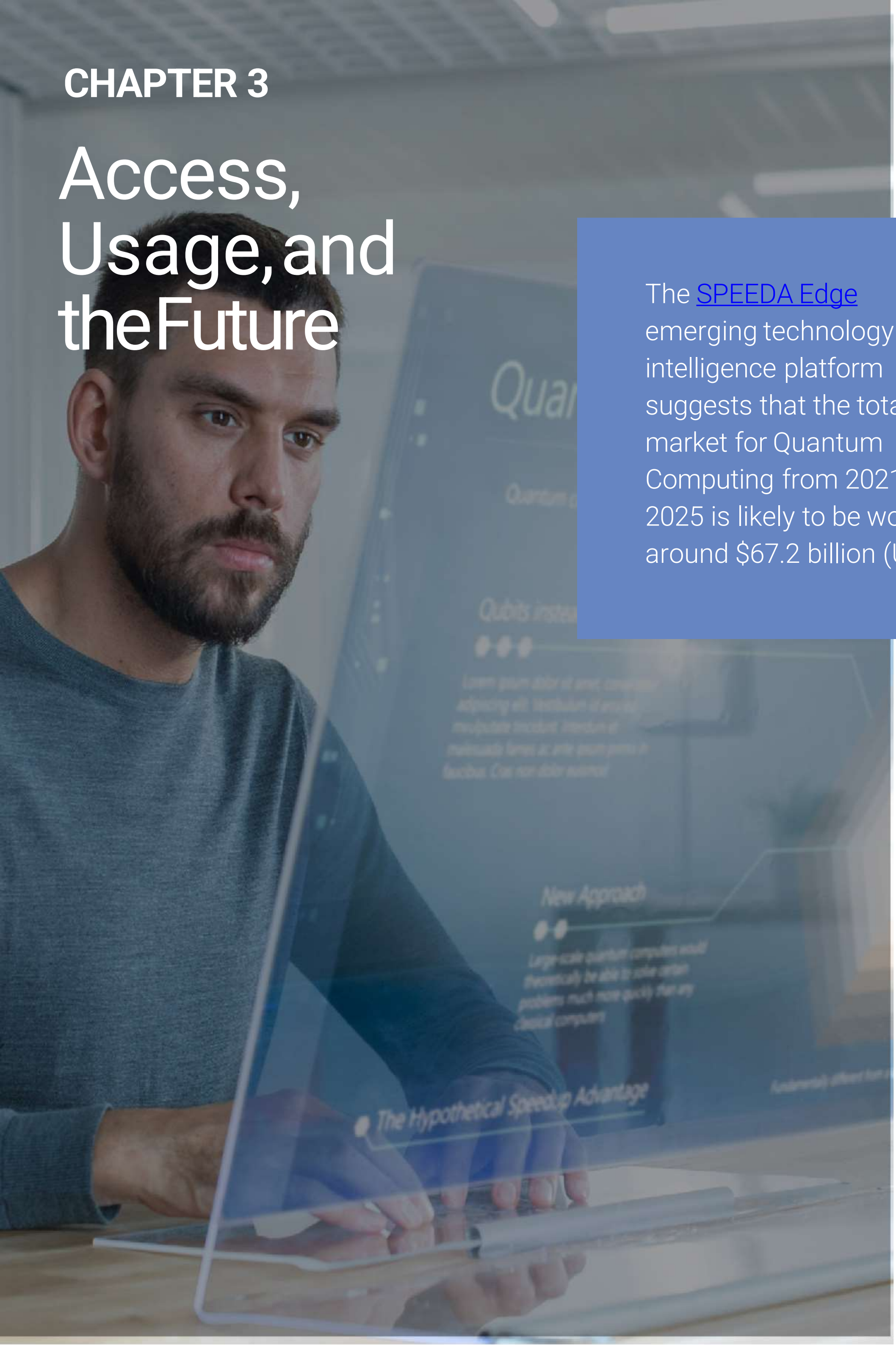
Recent developments, such as the rise of crypto-currencies and blockchain technology, have demonstrated this principle in action with great clarity.

Bitcoin mining, to use one example, requires blockchain calculations of great complexity, and we have seen cases of how investment in these new use cases has led to opening of new power generation facilities, recommissioning of others that have been closed down and risks of power shortages across the economy as a direct result.

Datacenters are now one of the leading causes of carbon emissions. At an estimated 3.7% of the total (according to the specialist consulting firm Climatiq), they now exceed emissions from international flights (steady on 2.4%) (see Lavi, Hessam 2022 footnote 3).

Quantum mechanics makes it theoretically possible for computing transactions to take place without losing information and therefore without generating heat at all. Tests in operational systems have demonstrated the truth of this. A quantum annealing system, using a cooled superconducting method requires 20 KW of electricity to reduce the system to the superconducting state. At that point, however, each calculation requires 20 fw (femtowatts) or one billionth of a watt.

In operation, quantum computers will use insignificant amounts of power to carry out vast numbers of calculations. As the fight against climate change intensifies, this technology has the potential to reduce power usage for computing as a whole, while also identifying solutions for managing economic and social priorities in what may become chaotic and disorderly climatic conditions.



CHAPTER 3

Access, Usage, and the Future

The SPEEDA Edge emerging technology intelligence platform suggests that the total market for Quantum Computing from 2021 to 2025 is likely to be worth around $67.2 billion (US).

ENGAGEMENT AND GETTING STARTED

The market size of quantum computing can be paraphrased as increasing on average by about $13.4 billion (US) annually through 2025. That makes it equivalent to the value of classic ultra-high-performance computers.

Yet, as we have seen, no single Quantum platform can yet be considered as stable or mature enough to have overcome all technical issues, most notably error correction. The market is led by two major hardware manufacturers: IBM and Google, which collaborate with a wide range of smaller specialists, including IonQ, a leader in Ion Trap technology, which is of the greatest interest to every player in this field. Given the complex research and development landscape and based on the knowledge gained directly from NTT DATA's own status as a key researcher, we have concluded that the most logical method for early engagement in this most fascinating but still emerging field is through Quantum as a Service.

THE SERVICE LED APPROACH

Both AWS and Microsoft offer Quantum services to any company that holds an existing service account. That makes engagement simple and comparatively low risk. Most important, it means that service users can be reasonably well-assured that the services they access will include the latest and most effective options for Quantum Computing at any specific moment.

Each major service provider includes a range of technologies, sourced from specialist vendors, with computation options managed by the provider to deliver the best outcomes for each given task. Variations exist when comparing the two types of service, as each provider has decided to invest in a slightly different blend of technologies.

Because of the AWS's leadership in cloud service market share with an exceptionally large user base, we selected to validate AWS services first. In addition, because of possible use cases such as integration with existing services running on AWS.

There is a certainly a strong need to make a reliable Quantum Computing service more widely available, and the growth in use cases demonstrates this clearly.

The ***global insurance industry***, for example, is preparing for an exponential growth in vehicle telematics data, as automotive insurance moves from actuarial to real-time data flows. Recent tests carried out on automobile vehicle data demonstrate the need for Quantum computational capacity, especially as the expected move to autonomous vehicles finally accelerates later in this decade[2].

In ***smart manufacturing***, major players, such as Volkswagen, are now employing advanced and improved quantum algorithms through standard programming interfaces. The goal is to accelerate and improve development of quantum algorithms, leading to faster, more accurate services to the industry.

Within the wider ***financial services*** industry, researchers at the Fidelity Center for Applied technology are developing proofs of concept for Quantum use cases. They include Quantum backends and building hybrid classic to quantum and quantum to quantum workflows. The joint PoC developed between Fidelity and Amazon Braket pushes the boundaries of what is possible with cloud-based Quantum Computer, potentially enabling to rapidly deliver innovative solutions to meet customer needs .

Most applications are currently related to research and proof of concept, reflecting the lack of maturity in the technology at present. Over the rest of this decade, however, we expect to see greater confidence in the service led approaches that are coming onto the market, with improved results across a growing number of industries.

As the need for computational optimization grows to deal with exponential increases in data, together with the need for real-time outputs and dramatically improved environmental performance, so the use of quantum in real-world applications will grow.

AMAZON BRAKET

In this final part of the paper, we want to focus on Amazon Braket, the Quantum as a Service offering from AWS. The name is based on the “ket”, the term used for individual quantum states, with Bra-Ket as the notation used to write the equations that describe such states and their interactions.

Amazon Braket today offers quantum services from a growing range of hardware options, using the quantum gating and quantum annealing methods. Each individual computing job can be supported by simulation and hybrid methods. Access to the service is extremely simple, being available to any account holder without a separate account required and without the need for up-front payments (pay as you go is the normal process).

Application development is simplified by removing the need to understand or have any detailed knowledge of which forms of quantum systems are to be used. This reduces the levels of financial commitment, human expertise and upfront risk required. The simplicity of the service is a highly attractive feature of the Amazon Braket service, and this is a factor in NTT DATA’s decision to investigate the options that Amazon Braket can offer, based on its large number of users and potential for integration with other services that are already running in AWS environments. The architecture can be seen in figure below.

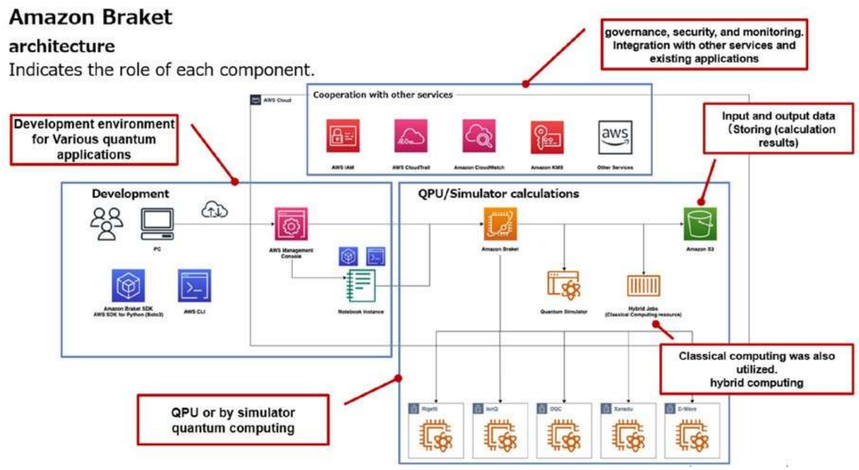


Figure 2: governance and security within the Amazon Braket environment

This diagram shows a normal process flow through the service:

- Development, for building the application and defining the problem to be analyzed.
- Simulation, including some classical computing, to refine the computational requirements.
- Quantum computing, which may use one or a number of different engines.
- At the top, the range of governance and management options.

As with all cloud-delivered IT services, security is a key issue and is shared between AWS and its individual clients on the long-established and well-understood basis: AWS ensures *security OF the cloud*, the client companies ensure security *IN the cloud.*

This means that AWS is responsible for protecting the infrastructure that runs all services offered in the AWS Cloud. This infrastructure consists of hardware, software, networking, and facilities that run the AWS Cloud services. Clients using the Amazon Braket service are responsible for carrying out the configuration work appropriate for each task, and for securing their own data up to the point of input to the Amazon Braket service.

The security layout is shown in figure below:

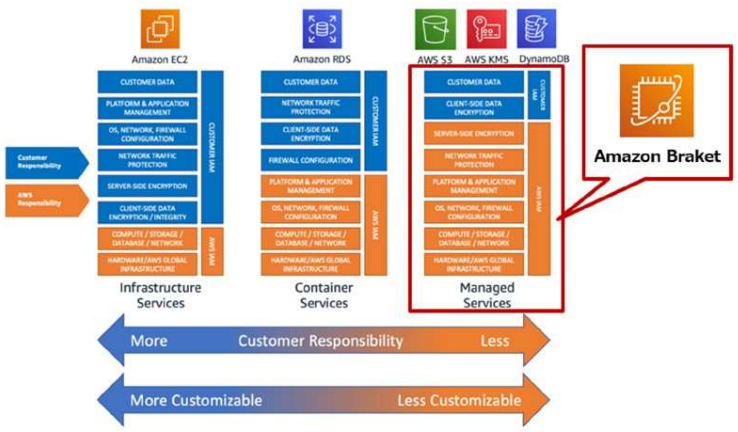


Figure 1: Braket architecture and component usage

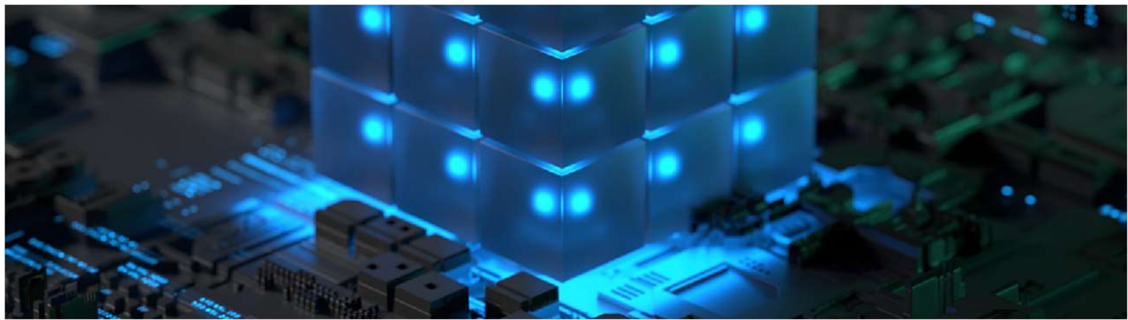
Backed by transparent methods for payment, data integrity and joint working, the Amazon Braket approach offers, in our opinion, the best option now available for accessing Quantum Computing in its present form on the market today.

NEXT STEPS

We certainly accept that Quantum Computing is in a transition stage right now, and a great deal of highly specialized research will be needed to make it an everyday, practical reality. We believe that 2030 is the target date by which Quantum may truly start to become used as the preferred means of computation, although the process will not be even, with specific use cases centered around the most complex problems taking precedence. Full replacement of classical computing with Quantum will certainly be a stage-by-stage process, taking at least a decade to complete.

Strategic investment at national level is helping to drive development of the most promising forms of Quantum Computing: notably Quantum Gate with Superconducting method (which is currently seen as the most promising area of development for the long term). To gain the benefits in the next 2 to 3 years, however, we will certainly use a hybrid method, in which a combination of NISQ and quantum/classical algorithms will be used. This is what makes the service approach, as exemplified by Amazon Braket so attractive. It has the practical capability to deliver at least some quantum benefits today, with a proven development roadmap that will see capability enhanced steadily over the next decade.

As the need to analyze data in unprecedented quantities become more urgent, with use cases related to complex calculations that simply cannot be handled by classical mechanics, so the case for Quantum Computing grows stronger.



About NTT DATA

NTT DATA is strongly placed to bring these benefits to its clients because we are engaged in original quantum research and have the scientific credentials to understand the concepts, their relative merits and the ways in which new use cases can be developed.

Contact us at