THE WHITE BOOK OF...

Quantum Computing

The definitive guide to understanding what quantum computing can achieve today and in the future

shaping tomorrow with you

FUJITSU

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Contents

Preface

What would ‘quantum ready’ really mean?
Quantum computing is becoming one of the buzz words of the decade – so now is a good time to step back and look at where we are on the path to a quantum future.

So far, quantum theory has gone from being obscure to accepted. Prototype devices exploiting quantum phenomena exist, and the world’s leading organizations have already moved beyond investigation and experimentation to proofs of concept. Business cases are being mapped out.

Although question marks still remain over the commercial and practical viability of quantum computing devices today, the lessons already learnt have sparked a new class of ‘quantum-inspired’ computing. The Quantum-Inspired computing delivers the advances in speed and scale hoped for from true quantum computers, but with none of the cost, energy and deployment hurdles being experienced by those devices today.

This White Book provides insight into how the drive to perfect processes using combinatorial optimization lies behind many use cases for quantum computers and how quantum theory led research that a quantum computing device might actually be possible and understand what quantum computing is. We would also cover various classes of quantum computers and quantum technology more broadly, before turning towards the business case for quantum computing in areas such as automotive manufacturing, financial services, the rollout of 5G telecoms networks and in drugs and materials discovery.

While quantum computing sounds promising it is important to understand the challenges – both technical and business - in the way of achieving those business cases, then review what the new class of quantum-inspired computing is, what it’s delivering, and look at who is already using this breakthrough technology.

Finally, having reviewed today’s panorama, we look towards the horizon to consider what quantum computing’s future direction might be, particularly in relation to machine learning.

We stand on the edge of a new age of computing.
This is the story of how we got here and what we do next.

Dr. David Snelling,
Fujitsu Fellow, Director - Artificial Intelligence Programs

“I would like to thank my colleagues Dr. Fritz Schinkel and Manju Annie Oommen for contributing and putting together this detailed document.”

Quantum-Inspired computing delivers the advances in speed and scale hoped for from true quantum computers, but with none of the cost, energy and deployment hurdles being experienced by those devices today.

1 Why Quantum?

Everywhere you look, there are more and more possible connections. There's even a new name to describe this: "hyper-connectivity". This ability to join up anything with an IP address in a so-called Internet of Things, means that optimizing the business processes that make use of all these connections is theoretically possible, with all the radical implications this implies for efficiency, quality and profitability.

Yet it is also tantalizingly out of reach. The number of possibilities surges to new heights with each new connection and has already gone well beyond the capabilities of conventional computing.

When major automotive OEMs began looking at optimizing traffic across a city or country for their new autonomous cars and mobility platforms, the calculations were just too big for any computer to process fast enough to take real-time traffic conditions into account. To give an insight into the scale of the problem - to find the shortest and/or least time consuming path of five pairs of start and destination points deals with 10^{100} possibilities.

In financial services, the desire to optimize short-term funds management or large portfolios of highly liquid assets in real-time involves many economic parameters which would be ever-changing – and this means that the size of calculations starts to grow exponentially. Therefore, the range of possible outcomes quickly spins beyond the reach of even the fastest supercomputers, and the opportunity for new, agile products and services is lost. Creating portfolios of assets that are not easily affected by market fluctuations, for example, has been problematic. Even with just 500 stocks, the number of possible combinations is 1.63×10^{150}.

These are not isolated cases. The same constraints – and opportunities for those who find a way through them – are replicated in utilities, pharmaceuticals and life sciences, materials and chemistry, retail and government. Which sums up to pretty much all industries.

The underlying thread is the need to find the optimum sequence in a process – more or less any process – to drive out any inefficiencies and improve productivity, responsiveness and service, or to decrease risk.

However, introduce variables in different dimensions and it becomes impossible to reach a workable answer quickly enough to gain any practical benefit. If 'impossible' sounds like hyperbole in the context of today's supercomputers, then consider that calculating the most valuable combination of just 40 from 100 items that could be carried on a trek in a knapsack could result in a number of possibilities exceeding one million times the number of stars in the universe.[1]

A new way of tackling these so-called 'combinatorial optimization' challenges is removing current constraints, thanks to the emerging new classes of quantum and quantum-inspired computing.

Unsurprisingly many Chief Technology Officers are taking a hard look at quantum computing. Though the popular topics associated with Quantum is cryptography, quantum chemistry, traffic route optimization, etc. Many of the areas being tested are essentially combinatorial optimization problems. For example, traffic route optimization and molecular similarity search, as a part of quantum chemistry. Hence, solving these optimization problems is looking more like it's leading to the next wave of disruption and is an opportunity higher revenue streams, leaving competitors in the dust. Hence the race towards making the most of the progress as innovators.

There are naysayers when it comes to quantum computing, with predictions for its commercial availability ranging from an optimistic five years to a more realistic 10 to 15 years – and even a pessimistic 'never'. Quantum computing may – when it eventually arrives – be able to solve the hoped-for challenges. But it's not here yet. As we'll see in chapter 5, quantum-inspired computing, on the other hand, is available today and delivers combinatorial optimization calculations with the speed, precision and scale of quantum computing.

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2 What is quantum computing?

The idea of a quantum computer goes back 40 years, when physicists familiar with quantum theory began to speculate whether it might provide the basis for encoding information.

In 1980, this led to the proposition by Yuri Manin of a quantum computer, an idea made more widely known by Richard Feynman during a lecture at the Massachusetts Institute of Technology (MIT) the following year. It was not until 1994, however – when MIT professor Peter Shor revealed he had developed an algorithm with the potential to decrypt all secured communications – that the quest for a quantum computer to process such an algorithm began in earnest.

Quantum theory is notoriously counterintuitive. So much so, that the original thinkers in this area – Albert Einstein, Niels Bohr, Werner Heisenberg and Erwin Schrödinger are the best known – actually doubted the logic of their conclusions. Even in the 1980s, the idea of a quantum computer was wildly speculative. Not many people outside of theoretical physics departments really believed that core phenomena in quantum theory, such as superposition, quantum tunneling and entanglement, were real, let alone something you could use to create new technologies. Schrödinger's cat, after all, was originally intended as a reductio ad absurdum – a formal means of disproving Bohr and Heisenberg's 'Copenhagen interpretation' of quantum mechanics, which included superposition.

Quantum theory evolved from the physics of light. In 1670, Christiaan Huygens suggested light moves in waves, and this was proven in 1801 by Thomas Young. Using a 'double slit' experiment, Young demonstrated that light produces diffraction and interference patterns when it passes through two slits in a partition, essentially much like the patterns made when you throw two stones into a pond and watch the waves interact.

Einstein was particularly concerned about an aspect of quantum theory called 'entanglement'

In 1905, Einstein's quantum theory of light proposed that light moves as tiny packages of energy, or quanta, introducing the duality of light – it behaves like both waves and particles.

This was confirmed when physicists turned back to Young's double slit experiment. These new double-slit experiments showed that, while light indeed creates wave-like interference patterns on a screen behind the slits, it is always absorbed at the screen at discrete points as individual particles (not waves), with the wave-like interference pattern only appearing via the varying density of these particles.

Einstein's light quanta proposition was taken a step further by Louis de Broglie in the 1920s, who postulated that if light behaves like particles, then particles can also behave like waves. This astonishing idea – wave/particle duality - was proven in 1927 by Davisson and Germer, also using double-slit experiments, although instead of light, they fired particles (initially electrons – later experiments extended the principle to atoms and molecules) at the slits.

As experiments progressed, strange phenomena within the quantum world began to emerge. By placing detectors at the slits, it was discovered that each detected light photon passes through one slit (as would a classical particle), and not through both slits (as would a wave). However, the very act of detection at the slits appears to collapse the light's wave function and eliminate the interference patterns that are seen when there is no slit detection.

Trying to interpret the results of the double-slit experiments, Bohr and Heisenberg evolved the Copenhagen interpretation. This was the prevailing theoretical explanation of quantum phenomena in the mid-1930s and says that a quantum system remains in an unresolved state (wave or particle, for example) called 'superposition', until it interacts with or is observed by the external world. When this happens, the superposition collapses into one or other of the possible definite states.

As experiments progressed, strange phenomena within the quantum world began to emerge.

Einstein was particularly concerned about an aspect of quantum theory called 'entanglement', which was discussed in a 1935 paper he co-authored with Boris Podolsky and Nathan Rosen – the so-called EPR Paper. This stated that if superposition persists until there is observation, then pairs or groups of quantum particles will remain in their original state (hence 'entangled') until there is an observation, no matter how far apart they eventually become. If this were true, then two entangled particles separated at opposite ends of the universe would instantly interact at the point of observation. In what came to be known as the EPR paradox, Einstein (and others) argued that what he famously called "spooky action at a distance" was impossible, which indicated that something remained to be understood about the Copenhagen interpretation.

Erwin Schrödinger was also unpersuaded. He argued that if objects in quantum superposition can be in two (or more) states at once, then a cat in a locked steel enclosure, with its life or death dependent on whether or not a radioactive atom had decayed and emitted radiation, could be either alive or dead – and that the outcome would only become known when the enclosure was opened.

Schrödinger was not a complete quantum skeptic, however, and worked to unravel the theoretical underpinnings. He later defined an equation that describes the evolution over time of physical systems affected by quantum mechanics – this is essentially a wave equation that determines the probabilities of the physical quantities of the system. Quantum theory is not deterministic like traditional physics, because in quantum theory everything has a probability. The solutions to the equation are waves of probabilities.

One consequence of the probabilistic uncertainty inherent in quantum theory is the complex concept of quantum tunneling. If particles are moving in smooth waves towards a barrier, then the wave function of any particle that hits the barrier will drop smoothly rather than abruptly, leaving a small tail on the other side – with a small but finite probability that it passed through the barrier – a phenomenon which is called quantum tunneling.

Different types of quantum computers

Despite the skepticism of Einstein, Schrödinger and many others, quantum mechanics has survived a century of investigation and is now considered established. So much so that we see it being applied today in experimental testing of various kinds of quantum computers to solve previously intractable problems at lightning speed.

It is the combination of superposition and entanglement that catapults us forwards in terms of computer processing speeds: not as a result of accelerating the computation, but rather by computing all possibilities at the same time. The challenge is to keep the computer in that state long enough to do the calculation.

In classical computing, each bit of information is unconnected to any other and must be processed as a one or a zero - in sequence – for example in addition, a bit is updated based on a bit from another input quantity and then, in sequence, updated based on the 'carry bit'. Rather than bits, as we understand them in classical computing, a quantum computer maintains a collection of entangled quantum bits or 'qubits'. These can represent a one, a zero, or any quantum superposition of those two qubit states. However, when qubits are measured, as set out in the Copenhagen interpretation, they always give a 0 or a 1 based on the most probable quantum state they were in at that time. Thus in a quantum computation, the qubits involved will have their probability of being 1 or 0 increased or decreased in accordance with the correct answer to the computation – or rather the most 'probable' answer as we are talking about a quantum system.

Quantum computers currently fall into two categories; **analog** and **digital**.

Within the **analog category**, are three further approaches known as:

Quantum simulation

– The concept first proposed by Manin and Feynman for the modelling of quantum systems that are difficult to study in the laboratory and impossible to model with classical computers. The proposal was that a quantum system with many particles could be simulated by a quantum computer using a similar number of quantum bits. Today, experimental quantum simulators have been realized on systems including ultra-cold quantum gases, trapped ions, photonic systems and superconducting circuits.[2]

Read more

Quantum annealing

– This finds the optimum solution in a finite number of possibilities (so-called 'combinatorial optimization' problems). Whereas traditional simulated annealing uses random 'thermal' fluctuations for convergence in optimization problems, in quantum annealing the addition of quantum tunneling provides a faster mechanism for moving between states and faster processing (see chapter 5 for more detailed explanation).

Read more

Adiabatic quantum computation

– This is a special process of quantum annealing. To find an unknown global minimum (ground state) of a possibly complicated energy function the process starts with a simpler energy function with a known solution. The adiabatic annealer is initialized with this energy function and the known ground state. Now the energy function is smoothly transformed to the energy function of interest. When this is done appropriately slowly then the system is in the ground state of each evolving mixture of the two energy functions (a consequence of the adiabatic theorem). At the end of this process it is in the ground state of the energy function of interest and this is the solution of the problem (see chapter 5 for more information).

Read more

Quantum Gate computing

– Quantum computers that use quantum logic gates, a basic quantum circuit operating on a small number of qubits, for computation. Constructing an algorithm involves a fixed sequence of quantum logic gates and a problem is encoded by setting the initial values of the qubits. Measurement collapses the qubits into one of the 'eigenstates', where each qubit is zero or one and classical computing norms come back into play.

Read more

Other quantum technologies

Quantum computing is a subset of a larger field of physics and engineering called 'quantum technology', which leverages quantum properties for practical applications.

Other branches of the field include quantum sensors, quantum cryptography, quantum metrology, quantum communication, and quantum imaging. Of these, quantum cryptography is an application of quantum computing aimed at factoring the large integers that form the basis of most modern secure systems. The other technologies, exploit a variety of quantum properties to achieve their functionality, but are beyond the scope of this white book.

First proposed in a 1997 book by Gerard J. Milburn, the quantum technology concept has since accelerated. In 2016, 3,400 scientists signed the Quantum Manifesto calling for a coordinated initiative between academia and industry to transition quantum technologies from the laboratory to industry.

The European Commission responded with a € 1 Billion, 10-year-long Quantum Flagship research and innovation initiative. Elsewhere, China is building the world's largest quantum research facility, with a planned investment of 76 Billion Yuan (approx. € 10 Billion) and in the USA, the U.S National Quantum Initiative Act - a ten-year plan for $1.25 billion in funding over the first five years - was signed into law on December 21, 2018.

In 2016, 3400 scientists signed the Quantum Manifesto calling for a coordinated initiative between academia and industry to transition quantum technologies from the laboratory to industry.

3 What are Enterprises expected to achieve from quantum computing?

CTOs are naturally intrigued by the possibility of unlocking the gains available from optimization with quantum computing.

BBVA, a leading Spanish banking group, has stated that "integrating the fundamentals of quantum mechanics into computer science will bring about a sea change in the depth and breadth of computing power." And at Fujitsu Forum Munich 2018, the CTO of a major global automotive OEM explained how he was there to discuss his organization's joint exploration of complex optimization problems together with Fujitsu. These were problems he described as "...unsolvable with linear upgrades of the technology we have today".

Manufacturing industry in particular has been quick to see and interrogate the possibilities of quantum computing. The challenge they face is existential. Author and economist Jeremy Rifkin put it like this: "25 years from now, car sharing will be the norm and car ownership an anomaly." Likewise, in the aerospace industry airlines are less interested in the price of an engine than the number of hours the aircraft spends in the air. The major engine manufacturers now price on that basis – fully aligning customers' commercial imperatives with their manufacturing offer.

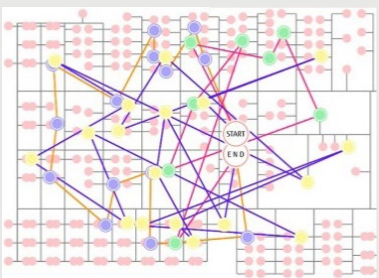
Confronted by new competitors working the car sharing space and interacting directly with the end user, automotive manufacturers have reacted to the arrival of Uber, Lyft, Waymo, etc., with their own moves. These embrace Mobility-as-a-Service (MaaS) and connected/autonomous vehicles, to create a direct end customer offer that is not mediated through traditional third-party dealerships in the motor trade.

"We want to gain an in-depth understanding of applications of this technology which could be beneficial to the company"

But the car manufacturers also quickly realized that the ability to bring real insight to the mobility platforms through traffic optimization was beyond the reach of current computing – sparking early investigation of the potential of quantum computing as a solution.

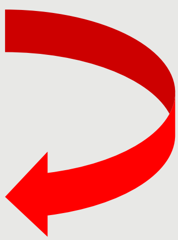
Volkswagen, to take one example, has announced that it is developing a smart traffic management system using quantum computers with the aim of increasing global transportation efficiency. In the words of Florian Neukart at Volkswagen's CODE Lab in San Francisco: "We want to gain an in-depth understanding of applications of this technology which could be beneficial to the company, including traffic optimization. Public transport organizations and taxi companies in large cities are highly interested in managing their fleets efficiently. Our quantum-optimized traffic management system could help make that a reality."

Picking Optimization for Factory Parts



Very complicated picking routes required experienced workers

Warehouse area: 1000m²
Number of parts: 3000



40% reduction

Digital Annealer provides optimum picking routes displayed on a tablet

Once quantum computers are mainstream, it is believed, then optimizing today's challenges such as city-wide, even countrywide road traffic routing, will become routine.

What these progressive thinkers are reaching for is the ability to improve business processes by solving a class of problems known as 'combinatorial optimization' – the process of identifying the optimal solution by evaluating each possibility from a finite but extremely large set of options. In other words, intractable problems.

Until now, in tackling any combinatorial optimization problem, there has been a trade-off between precision and risk. Seeking high precision used to imply the need for more time to calculate the answer, while accepting a 'good enough' answer introduced an increasing amount of risk and the need for a security buffer. The more precise a calculation you can achieve, the more cost-efficient the final process will be, leading to a game-changing opportunity to gain a competitive advantage.

As an analogy, before the advent of sonar and GPS, when sailors manually calculated the clearance under the ship at any point in a tidal pattern, it was wise to leave a margin of error, even at the expense of a slightly longer journey. If the calculation was not precise enough, the cost and inconvenience of running aground was not worth contemplating.

If quantum computing can be made to work, the balance in this equation shifts – because compute power is expected to provide a precise view, it removes the need to build in much of a margin of error – and it's in this way that savings are achieved.

It is this potential to overcome the limitation of conventional computing that explains why many of the world's major enterprises are now investigating quantum computing. In automotive manufacturing, besides VW, other major OEMs including Daimler and Ford have announced quantum computing programs. Pharmaceuticals companies, including Amgen and Biogen and chemicals companies are looking at areas such as molecular matching for new drug and materials discoveries. Utility companies are aiming to optimize ROI from new asset investment, while banks such as NatWest and BBVA and insurance companies are seeking to optimize portfolio and credit risk. Governments too are fascinated by the potential to achieve climate change targets faster, through optimization of transport systems to reduce pollution and waste from traffic jams.

Future potential

The potential of quantum and quantum-inspired computing to overturn paradigms that stretch back decades has really gripped the imagination of visionaries - the 'way it has always been done' can now be ripped up.

For financial services organizations, the main source of disruption comes from the ability to do things that were totally impossible up until now. We saw in chapter 1 how even a relatively small asset portfolio can involve a universe of possible combinations beyond the optimization powers of conventional computers. Quantum computing makes daily rebalancing of asset portfolios for optimized returns a possibility, with a resulting shift in the whole business sector requiring new business practices and transaction pricing models.

In aerospace, manufacturers are investigating potential of applying quantum technologies to challenges such as aircraft climb optimization, wingbox design, aircraft loading optimization, satellite imagery analysis and the development of new ultra-durable materials for aircraft. Optimizing the loading, routing and scheduling of aircraft has enormous potential commercial benefits for an industry where cost competition is fierce and environmental pressures are mounting.

As we have seen, the automotive sector turned to quantum because of traffic optimization in mobility-as-a-service and for autonomous vehicles, but has quickly branched out from there as it gained experience with quantum computing and the quantum-inspired Digital Annealer. Battery development is in the spotlight, with the search on for high-density designs that could dramatically expand the capacity of batteries used in everything from portable electronics to vehicles. The time is right: Improvements in battery density have been running at just 5 to 8 percent annually.

In utilities, telecoms network operators are exploring quantum computing to optimize the deployment of expensive assets in current 4G and future 5G networks. The same principles hold good for power transmission networks, and water and gas supply networks.

In life sciences and healthcare, quantum optimization will lead to the faster discovery of new drugs through molecular similarity searching carried out in moments rather than months, and to new, more effective, less toxic combinations of cancer therapies that can be simulated using quantum techniques in a fraction of the time currently needed.

And governments will turn to quantum computing to help solve vital societal challenges such as lower carbon emissions and better air quality, as well as economic challenges such as modelling the impact of budget changes.

Battery development is in the spotlight, with the search on for high-density designs that could dramatically expand the capacity of batteries used in everything from portable electronics to vehicles

4 Challenges of quantum computing: why is it not ready yet?

Technical challenges

Despite initial skepticism, we now see various kinds of quantum computers being used for experimental testing – and the potential is awe-inspiring. The only problem is, it remains some distance in the future.

One thing is clear: today quantum computing remains experimental, expensive, complicated and temperamental, and requires very specific operating conditions in order to compute and provide output – including power and cooling requirements that are simply beyond the reach of even high-end data centers. As MIT professor Isaac Chuang puts it: "The thing driving the hype is the realization that quantum computing is actually real. It is no longer a physicist's dream—it is an engineer's nightmare."

In order to produce the correct output for a problem, quantum bits must remain in a quantum state at near absolute-zero temperatures, free from any outside interference, including cosmic rays or magnetic fields. Get this wrong and the qubits collapse out of their delicate entangled state, losing all quantum acceleration and of course also rendering any further calculation impossible. To emphasize just how difficult this is, when an IT company unveiled a 50 qubit quantum computer to great acclaim in late 2017, it featured the ability to preserve a quantum state for an industry-record time: 90 nanoseconds.

The fragility of these quantum states makes quantum computing prone to error and creates a corresponding need for error correction. This consumes a sizable proportion of an already sparse pool of qubits, making it impossible to solve large scale problems and hence quantum computing has been restricted to research purposes only.

Considering where we started from, 50 physical qubit quantum computers are a great achievement.

What this has also led to is the maturity of quantum algorithms, which have shown significant progress when tested on classical computing architectures as well. However, the quantum computers available today are unable to take advantage of these quantum algorithm advances. For large-scale combinatorial optimization problems, existing quantum devices fail to give a better result than when quantum algorithms are simulated on classical computing system as the problem scales to a real-world data set. In quantum annealers, the problem is called 'chain break' – essentially the problem which is embedded breaks as the scale increases, resulting in sub-optimal solutions or errors.

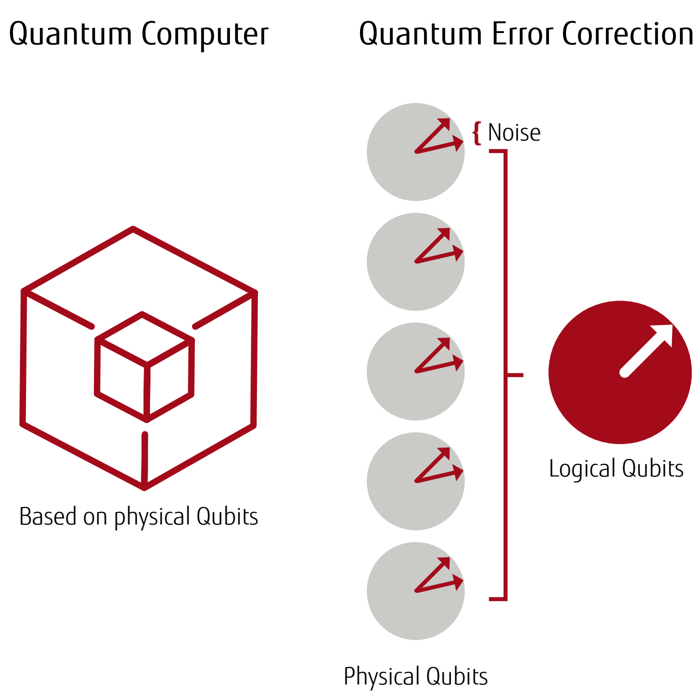
One cause of these challenges is the frequent misconception about physical and logical qubits. Quantum algorithms are described by the logical qubits required, which may vary from 20 qubits to 50 qubits, or even 1,000 qubits, depending on the scale of the problem and complexity. However, when there are announcements on quantum computers that supports 50 qubits or 100 qubits, these are essentially physical qubits which do not correlate directly to logical qubits due to two factors: 'noise' and the fact that qubits are not universally entangled, which brings in the requirement for error correction.

In life sciences and healthcare, quantum optimization will lead to the faster discovery of new drugs through molecular similarity searching carried out in moments rather than months, and to new, more effective, less toxic combinations of cancer therapies that can be simulated using quantum techniques in a fraction of the time currently needed.

The correlation from physical qubits to logical qubits therefore depends on the quality of the qubits or circuits. Today, based on the systems available in the market – 1 logical qubit can require between 100 to 10,000 physical qubits. So, potentially solving a real-world scale problem could demand a scale of 1,000,000 physical qubits or greater.

To put this in perspective, at the TCS Quantum Symposium held in Bombay on April 7, 2019, test results showcased on real world quantum computers on computational chemistry was as small as two to four atoms. The quantum algorithms performed much better on classical computing systems – re-establishing the fact that quantum computers are simply not ready yet and we are still trying to find the best way to create a less error-prone quantum computer.

The correlation from physical qubits to logical qubits therefore depends on the quality of the qubits or circuits.



Business planning challenges

For business strategists, the increasing volume of noise around quantum computing poses some specific challenges.

The first concerns timing. While investment decisions on superconductivity quantum hardware are still some way off, it is clear that many major global players across multiple sectors of the economy are already well down the path of investigating the potential of quantum computing. They have already looked at possible use cases and opened dialogue with partners and possible future suppliers.

But many have not yet explored the possibilities. This might be a calculus involving possible costs and likely rewards, or it might be that the subject still just seems too much like science-fiction for some corporate boards. Either way, this is a risky strategy when others are comparatively deep into their programs – with disruptive new products, services and processes already emerging (see quantum-inspired computing, below, chapter 5).

Another challenge is knowing what to investigate. In some areas – discussed in chapter 3 - there are specific problems that have prompted quantum programs. But generally speaking, because these optimization calculations have not been possible until now, nobody has yet had enough time to imagine what and where the possibilities might be.

And cost will, of course, be a factor. While the eventual commercial cost of quantum computing is currently hard to scope with any precision, given the extreme operating conditions needed and the sheer complexity of the engineering, it is not going to be cheap.

When these engineering, cost and business barriers to quantum computing are combined, there are solid grounds for inertia. Except, there is now an opportunity to build experience and know-how about quantum software using the FUJITSU Quantum-Inspired Computing Digital Annealer to create a bridge to quantum and to gain optimization insights and leadership.

...many major global players across multiple sectors of the economy are already well down the path of investigating the potential of quantum computing.

5 What is quantum-inspired computing?

The differences between simulated annealing, quantum annealing and digital annealing

The term 'quantum annealing', discussed in chapter 2, takes its name from an analogy in metal production.

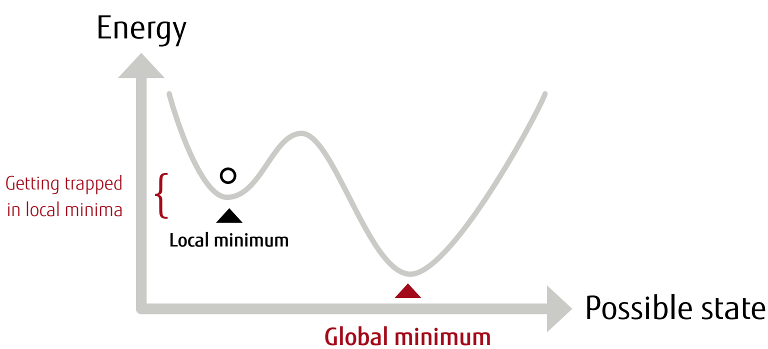
Since antiquity, metalworkers have used forges to heat and hammer all kinds of metal products to improve quality. This process, called annealing, is still used in steel production and causes layers of iron and other metal atoms to mesh together very tightly. In physics, models describe this as a crystal of low inner energy, a state which is hard to change and which, for example, makes a sword blade extremely hard.

This idea of energy minimization in metal annealing was then generalized to a 'simulated annealing' algorithm used to solve a wide range of optimization problems. When the algorithm has a target function (for example, energy) and a range of possible outcomes, annealing is looking for an optimal state, which in this example would be minimal energy. Simulated annealing finds this by a random 'walk' through the possible outcomes while simultaneously cooling down the system.

quantum annealing finds the global minimum more quickly and solves the optimization problem

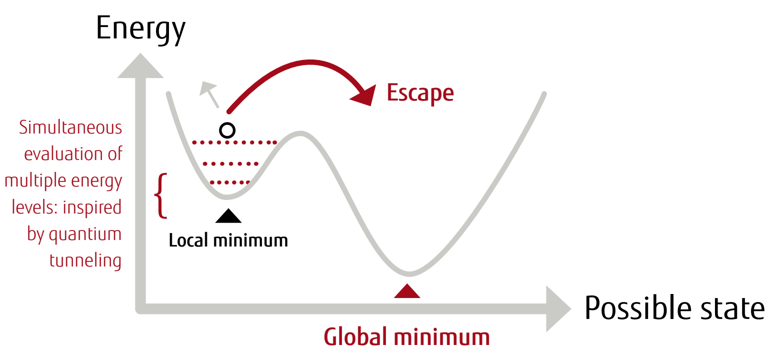
If we slow this right down for the purposes of explanation, what happens is that the simulated annealing algorithm starts with a high energy and temperature and randomly takes a step in some direction to one of the possible outcomes. If the energy measured at this second step is lower than at the starting step, then it is accepted. The system temperature is now a little lower and the algorithm takes the next random step.

If that step leads to a higher energy measurement, then it could also be accepted. The decision is made by a random experiment, where the acceptance probability decreases with higher energy measurements and lower temperatures. Within this process, some steps will end with a new minimum energy. These may be 'local minima' – the lowest found in that round of measurements, or they might be the lowest result possible from the entire field of possibilities, which is known as the 'global minimum'. However, the current existing architectures often get trapped in the local minimum and leads to more time required to obtain a sub-optimal solution.



In 'quantum annealing', the practical difficulties of avoiding acceptance of local, rather than global minima in annealing computations is largely overcome by one of the quantum phenomena we looked at in chapter 2 - quantum tunneling. Because of this property, the system can tunnel through every finite barrier without having to go to a higher energy. This is because the ground state (in our example, the lowest energy level) exerts the strongest attraction. Therefore, quantum annealing finds the global minimum more quickly and solves the optimization problem.

Fujitsu's scientists were first in the world to react to the realization that the annealing algorithms being developed for both conventional and quantum computers could be applied with great effect, as long as the hardware is capable of providing the acceleration required and identify a way to escape the local minima – this is what would become 'digital annealing'.

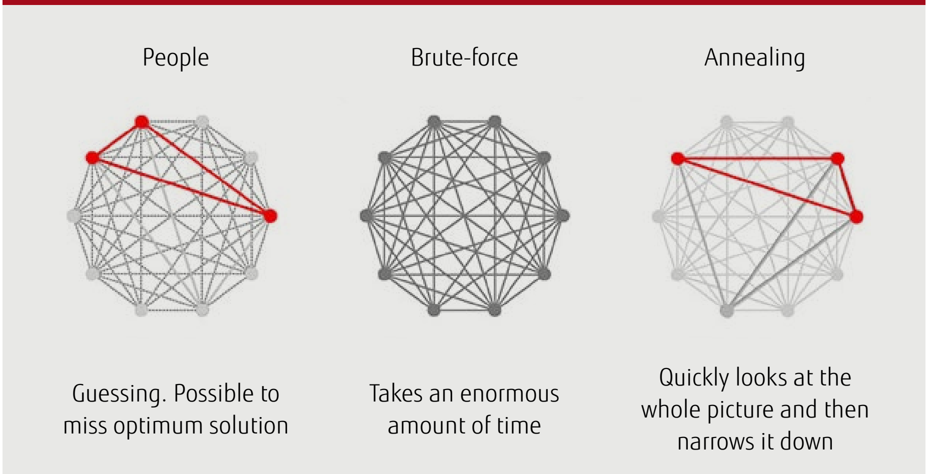


"Fujitsu's Digital Annealer architecture... uses a digital circuit design inspired by quantum phenomena"

Today's quantum annealers suffer from limitations in solving large scale problems due to the limited number of connections between qubits. Fujitsu's Digital Annealer architecture, on the other hand, uses a digital circuit design inspired by quantum phenomena with logical connections across all bits. It can solve large-scale combinatorial optimization problems very quickly and – hugely important – more accurately than quantum annealing with its limited qubit connections. As we saw in chapter 3, any reduction in precision implies higher risk or cost, making digital annealing not just more practical than quantum annealing, but more relevant for business decision making too.

A convenient way to conceptualize the Digital Annealer is as a special accelerator to speed up combinatorial optimizations – where it is always likely to be used with conventional hardware in a hybrid environment. It is important to emphasize that it is not true quantum computing and therefore does not suffer from that technology's engineering and practical constraints:

Principles of Annealing



- Unlike true quantum computing, it is commercially available today and not at the prototype stage.
- The Digital Annealer operates at data center temperatures and does not need special cooling: in other words, it operates with digital circuits at room temperature, and fits into a data center rack – or can be accessed via the cloud – without needing any specific expertise or a complex infrastructure to function.
- It utilizes the same algorithm in use in quantum annealers – co-created with Fujitsu's partners Toronto University, which has a leading research position in the field, and 1QB Information Technologies (1QBit), based in Vancouver, Canada, the leading commercial player in quantum software. This algorithm is compatible with those being developed for true quantum annealing computers, meaning that solutions developed with Digital Annealer today will be compatible with quantum computers, when these reach bigger qbit sizes, connectivity, and precision.
- And yet, for combinatorial optimization calculations – one of the core advances promised by quantum computing – the Digital Annealer delivers superior results to those currently available using true quantum devices.

Business combinatorial optimization challenges being solved today with Digital Annealer

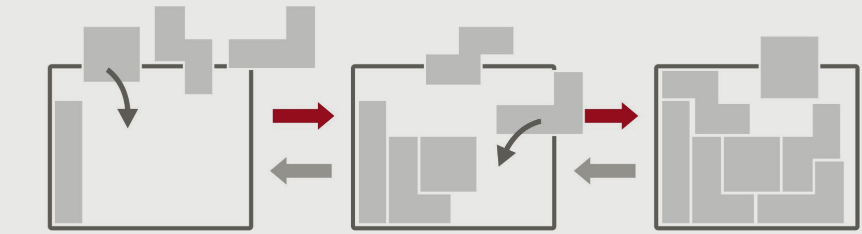
Combinatorial optimization has not just suddenly appeared as a challenge – it has always existed. Once handled by a series of educated guesses, the arrival of digital computing allowed more refined approaches, such as the so-called 'Monte Carlo method', which involves repeated random sampling.

Clearly better than guessing, even supercomputer-driven optimization is still relatively slow: we looked at some examples earlier, e.g. the knapsack problem, where the exhaustive calculation durations are not measured in minutes, hours or even days, but eons.

All business processes have the potential to be optimized – but this is only meaningful if the results can be obtained quickly enough to take commercial or organizational advantage. Now this is possible with digital annealing, the ability to uncover and leverage efficiencies and insights will bring profound change and advantages in all sectors of the economy and government.

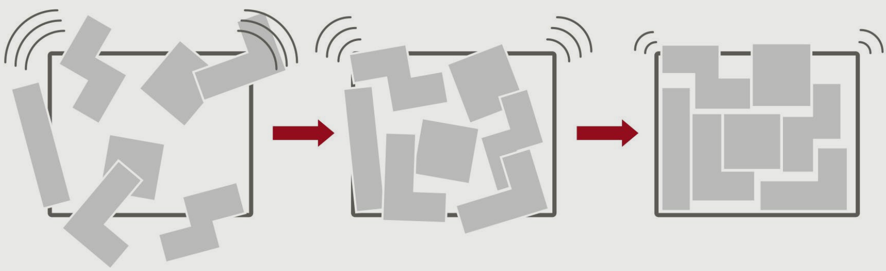
Conventional Method

Put the pieces in order; step back if a failure occurs



Annealing

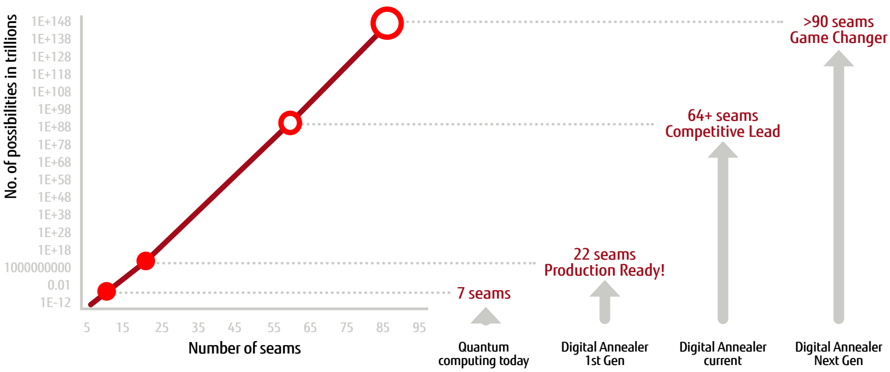
Shake, and the pieces fall into place



Using Fujitsu's new quantum-inspired Digital Annealer, combined customer-Fujitsu teams have already co-created solutions to optimization challenges in automotive manufacturing, including job shop scheduling, engineering design and just-in-time manufacturing optimization for robot positioning for chassis welding, which, as we will see, has a significant impact on manufacturing efficiency and cost.

One task for an automotive manufacturer is to calculate the best possible path for production seaming robots setting out from and returning to their base positions. Solving this optimization challenge has resulted in a higher vehicle throughput without investment in additional resources.

Currently, prototype quantum computing solutions addressing this challenge are able to compute optimization routes for about seven seams. Working with Fujitsu Digital Annealer, 64 seams trip can be calculated. This increase from seven to 64 seams is not just nine-times the number of seams. The number of possible trip combinations to choose from increases to more than 10^{100}, which is far beyond the assumed number of atoms in the whole universe.



This has resulted in production of more vehicles with the same resources and hence a reduction in paint-shop costs – which account for between 30 and 50 percent of automotive OEM's manufacturing costs.[3] Optimization in these areas can provide significant cost benefits and will be truly transformational for the industry. This is just the tip of the iceberg.

Fujitsu has also applied this solution in its own factories, where the use of Digital Annealer has reduced workers' traveling distances by 45 percent per month, with a consequent reduction in non-productive time.

With quantum computing still probably between 10 and 15 years away, it is now both possible and advisable to build a bridge to the quantum future.

Away from manufacturing, in the world of financial services, real-time optimization with the Fujitsu Digital Annealer has many applications for banks and insurance companies. In credit risk assessment of individuals and companies, it reduces risk by increasing the correlation of credit evaluation items while improving efficiency by reducing the number of credit characteristics to evaluate. Real time interest rate swap optimization in derivatives trading is another high gain option.

Other possibilities for digital annealing in financial services include calculating the optimum amount of cash and the most efficient route for ATM replenishment. Cash replenishment accounts for up to 60 percent of ATM network operating costs and optimization would improve profitability significantly at a time when ATM network operations are under pressure. Furthermore, cash left in ATMs unnecessarily is not in the bonded warehouses that allow banks to collect interest on their reserves – this is a huge part of the potential value of improving cash management.

In financial services, Fujitsu has successfully concluded a loan portfolio management Proof of Concept (PoC) with Commerzbank's research and development unit, Main Incubator GmbH, leveraging the Fujitsu quantum computing inspired Digital Annealer. Focusing on receivables from vehicle leasing contracts, the PoC optimized the selection of several thousand vehicle leasing assets for a securitization portfolio. Critical factors taken into simultaneous consideration included regulatory requirements, absolute volume limits and percentage limits for specific asset characteristics needed to achieve greater risk diversification.

And using Fujitsu's Quantum-Inspired Digital Annealer, NatWest bank has completed a highly complex portfolio risk optimization calculation that needs to be undertaken regularly by the bank, at 300 times the speed of a traditional computer while providing an even higher degree of accuracy.

In the search for new substances and to develop new drugs, chemical and pharmaceutical laboratories use molecular similarity searching, which partially extracts molecule characteristics. Digital Annealer-powered research is able to explore entire molecular structures without relying on extraction, thereby enabling accurate, instant similarity searching and faster, potentially disruptive new product development.

Early modeling suggests that digital annealing holds the potential to reduce traffic congestion by up to 40 percent, by dispersing traffic to less congested routes.

TORAY Industries, Inc. successfully tested Digital Annealer to accelerate drug discovery and biotech research. Its approach is to optimize molecular structure stability with Digital Annealer by predicting the most stable protein side-chain structures, with the aim of improving stereochemical prediction accuracy in target protein research. Elsewhere in this sector, Fujitsu is also running a joint research with Toronto University in advanced medical care for cancer treatment to improve cancer radiation therapy.

In transport and logistics, Japan Post Co. Ltd. has been able to reduce its delivery fleet in a single city from 52 to 48 trucks. In collaboration with quantum software company, A*Quantum, Japan Post has leveraged the Fujitsu Digital Annealer to optimize transportation route combinations, truck types and cargo loads. The result has been the capacity to shrink the delivery fleet and reduce costs, while achieving faster delivery times and truck loading efficiency.

And in the public sector, cities and national governments are urgently looking to address the issue of traffic optimization. The potential benefits are significant: better air quality means lower levels of respiratory and other diseases, and increased citizen wellbeing. Lower carbon emissions feed through to national targets on emission reductions, enabling governments to focus their spending on other vital policy areas. More efficient journeys will raise productivity, reduce frustration and encourage economic growth.

The Digital Annealer's ability to perform successive, real-time calculations on unbelievably complex challenges stands head and shoulders above today's computers. These struggle to perform the calculations at all. Early modeling suggests that digital annealing holds the potential to reduce traffic congestion by up to 40 percent, by dispersing traffic to less congested routes. This is what Digital Annealer could achieve with its first generation, with only 1024 bits, calculating five pairs of start and destination points, involving 10^{100} possibilities. As the scale of the problem increases, the Digital Annealer solution also requires more scale, and hence a new 8192 bit solution has been released and a 1,000,000 bit scale is expected to be released in the future.

Quantum-inspired, highly-parallel capabilities enable the Fujitsu Digital Annealer to almost instantly find near optimal combinations of massively complex, previously unmanageable combinatorial optimization problems.

The Digital Annealer's ability to perform successive, real-time calculations on unbelievably complex challenges stands head and shoulders above today's computers.

Performance comparisons for real world problems

The power of the Digital Annealer lies in Fujitsu's quantum-inspired digital architecture that leverages innovations in ultra-high-density circuit integration and high-performance processing.

Digital Annealer is delivered to customers as an end-to-end solution, deployed anywhere from cloud to edge. The Digital Annealer solution today supports an 8,192-bit fully-connected architecture with a promising roadmap to support a 1,000,000-bit scale solution. The 8,192-bit Digital Annealer solution not only comes with a high precision of 64 bit (the highest accuracy available in the market) but also with the capability of partitioning. This means – depending on the problem scale, you can configure the system in different configurations as here:

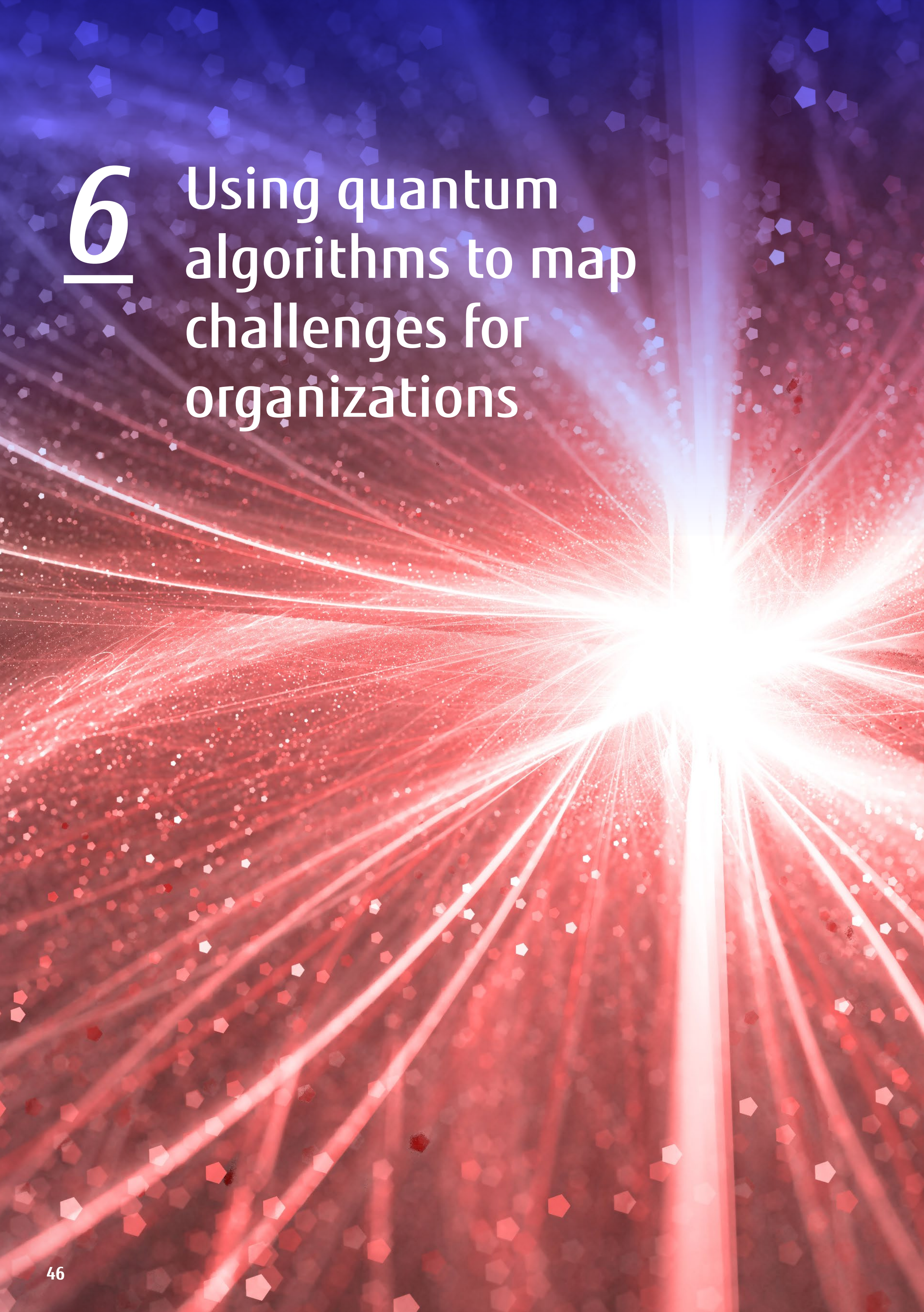
> 1x 8,192 partition, 2x 4,096 partitions,
> 4x 2,048 partitions, 8x 1,024 partitions

And each partition can run one problem at a time. This gives Digital Annealer a unique advantage of parallel processing of different problems set on different scales at the same time.

Because it is available now, Digital Annealer creates a practical bridge to the future world of true quantum computing, whenever that time comes. It offers the same near-instant solution of combinatorial optimization challenges that quantum annealing will provide, using similar algorithms, so that there is no requirement to "relearn" annealing algorithms at a future date when quantum annealing matures sufficiently. And when it comes to performance, Fujitsu Digital Annealer is:

- Up to 10,000 times faster than industry standard compute systems [4]
- 12 Moore's Law generations ahead of current processors
- Data-center and room temperature compliant – avoiding the very high energy and complexity costs of advanced cooling systems needed for quantum computers
- On a roadmap to release 1 million-bit scale to disrupt the market

6 Using quantum algorithms to map challenges for organizations



Fujitsu applies certain classes of algorithms on Digital Annealer, which are known to be suitable for quantum style computation. Furthermore, the following are easily converted to the form of a Quadratic Unconstrained Binary Optimization problem, or QUBO for short – the input format of all problems solved on the Digital Annealer:

Graph Coloring

– Assigns labels or 'colors' to elements of a graph. In its simplest form, it is a way of coloring the vertices (or nodes) of a graph such that no two adjacent vertices have the same color - this is called 'vertex coloring'. Other categories of graph coloring using similar techniques include 'edge coloring' and 'face coloring'.

This technique can be applied to scheduling, where jobs are assigned to specific time slots to avoid resource duplication or unavailability. The corresponding graph contains a vertex for every job and an edge for every conflicting pair of jobs. Practical examples include assigning aircraft to flights, and bandwidth allocation for cellular mobile and radio stations. Other applications of graph coloring are pattern matching, sports scheduling, designing seating plans, exam timetabling and the scheduling of taxis.

The Knapsack problem

– As we saw in chapter 1, knapsack computations quickly run away to mind-boggling complexity. Originally described by the mathematician Tobias Dantzig in 1897, the knapsack problem often arises in resource allocation where there are financial constraints and is studied in fields such as combinatorics, computer science, complexity theory, cryptography, applied mathematics and even fantasy league sports.

In terms of use cases, this algorithm can be used to find the least wasteful way to cut raw materials, the selection of investments and portfolios, the selection of assets for asset-backed securitization, and generating keys for knapsack-based cryptosystems.

Minimum k-cut

– This algorithm looks for a set of edges that would cut a graph to the minimum number (k is a constant number) of connected components. These edges are referred to as k-cut and the ability to optimize partitioning in this way has applications in VLSI (very-large-scale integration) circuit design, data-mining, communication in parallel computing and finite elements. Finite element method (FEM) solves engineering and mathematical physics problems such as structural analysis, heat transfer, fluid flow, mass transport, and electromagnetic potential.

Graph similarity

– Graphs are commonly used to encode structural information, and graph similarity is an important algorithm with applications in several fields of science, engineering and data analysis including computer vision and pattern recognition.

Solution Delivery

Fujitsu compute service

– To enable customers to leverage these algorithms, Fujitsu has created a Digital Annealer service, which provides solutions to any customer challenge that can be translated into a combinatorial optimization problem. And all this without needing the complex wrap-arounds associated with quantum computing, such as cryogenic cooling systems. This service is fully compatible with existing architectures and therefore fits into existing business workflows and processes.

Fujitsu consulting service

– The engagement model follows a fast, straight-forward three-step process that starts with a consultancy-led approach to identify the business challenge to be solved jointly and whether that translates into a combinatorial optimization calculation. If it does, in the second step Fujitsu's solution support team maps that challenge onto a mathematical model called Quadratic Unconstrained Binary Optimization (QUBO). This QUBO is then technically implemented and fine-tuned for the digital annealing algorithm. This then runs on the Digital Annealer service to provide the precise answer to the problem in seconds or minutes – depending on the size of the problem. In the third and final step, Fujitsu operates the customer's new Digital Anneal application, providing support and quality assurance of the system.

Quantum-Inspired Optimizations Services

– Fujitsu offers a range of optimization services based on use cases which range across industry segments – from portfolio risk optimization to traffic route optimization, through to planning flights for airlines and testing molecular similarities for drug discovery, optimization of production and assembly lines or optimization of infrastructure investment.

7 Preparing for the future

Fujitsu Digital Annealer has been described by independent analysts as a unique opportunity to preempt quantum computing and achieve the first stage benefits of optimization today, working within current data center constraints. They talk about creating a 'bridge' to the quantum future – getting the benefits of combinatorial optimization today while also learning how true quantum computing can be applied to operations in the future.

We've looked at examples of how organizations are applying quantum and quantum-inspired computing to use cases today and some of their ideas for the immediate future. We have also seen in chapter 2 how governments – China, the EU and the USA – have created very large-scale quantum technology initiatives to accelerate the transfer from lab to commerce.

When constraints previously regarded as unquestionable are suddenly removed – as they have been in the case of combinatorial optimization – then it is extremely difficult to see the long-term implications.
Did Einstein, Bohr, Heisenberg and Schrödinger imagine that their theoretical investigations of a new quantum mechanics would result in devices capable of instantly selecting the optimum solution from among quintillions of possibilities?

Artificial Intelligence (AI) has so far been mostly linked with relatively 'simple' machine learning

If we look towards the horizon, we can discern the new field of quantum machine learning at the intersection of quantum physics and machine learning. Right now, that applies to machine learning algorithms for the analysis of classical data executed on a quantum computer. This is usually a hybrid method that involves both classical and quantum processing, where computationally difficult subroutines are outsourced to a quantum device.

Quantum machine learning also extends to a branch of research that explores methodological and structural similarities between certain physical systems and learning systems, in particular neural networks. For example, some mathematical and numerical techniques from quantum physics are applicable to classical deep learning and vice versa.

Artificial Intelligence (AI) has so far been mostly linked with relatively 'simple' machine learning or the more complex neural networks underlying deep learning. The next step is the rise of alternative algorithms such as Generative Adversarial Networks, in which one generation of AI is trained by another. Although these will probably not be rolled out in production environments before 2021, quantum and quantum-inspired computing will increasingly be needed to cope with the complexity and speed requirements involved.

With quantum computing still probably between 10 and 15 years away, it is now both possible and advisable to build a bridge to the quantum future. Quantum-inspired computing available today. The Fujitsu Digital Annealer makes this practical and opens the door to the next wave of disruption coming from combinatorial optimization.

1. Single items have interdependencies. For example, as a stand-alone item such as a box of nails has a low value, but this increases when combined with a hammer. The number of stars is assumed as being 10^{22}.

2. Nature Physics Insight - Quantum Simulation, nature.com. April 2012

3. Assessment of Automotive Coatings Used on Different Metallic Substrates, W. Bensalah, N. Loukil, M. De-Petris Wery, and H. F. Ayedi, https://www.hindawi.com/journals/ijc/2014/838054/

4. The performance comparison was conducted by evaluating the quadratic assignment problem (QAP) on the Digital Annealer against a general purpose, multi-core, Xeon multi-processor system.

...it is now both possible and advisable to build a bridge to the quantum future...

For more information on the steps to Digital Annealer, go to:

www.fujitsu.com/DigitalAnnealer