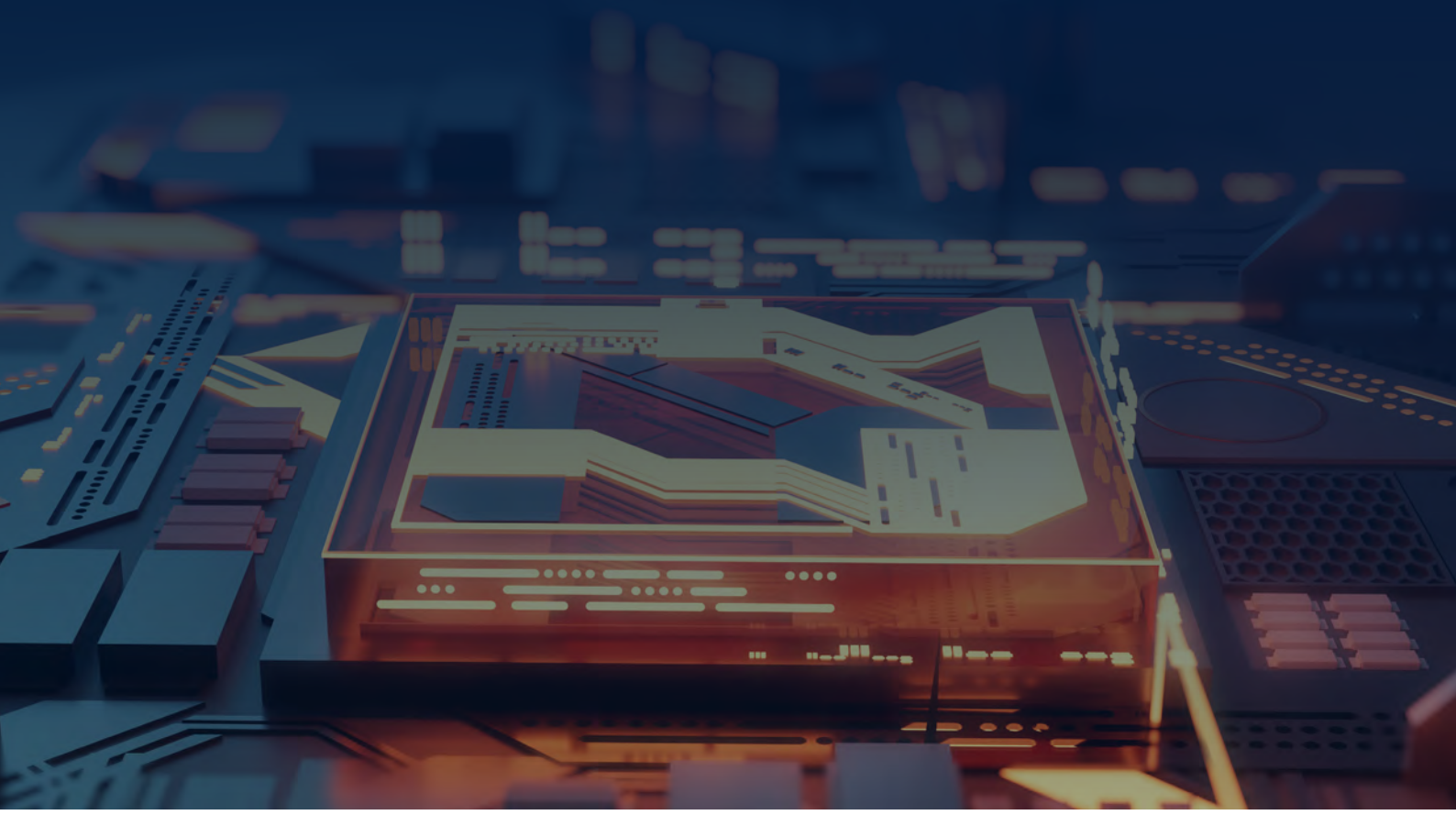
UK FINANCE

THE QUANTUM OPPORTUNITY

May 2021



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INTRODUCTION

Computers have unquestionably transformed the financial world. Each innovation, from cloud computing to artificial intelligence, opens new opportunities and changes the way the industry does business. Quantum computing is an emerging technology that promises a new generation of transformation and disruption within the financial services industry.

Only a few years ago, quantum technology was obscure, and unknown outside technical circles. Yet, with recent advances in technology, it's now impossible to ignore quantum computing.

> "Quantum computing has the potential to disrupt financial services profoundly in the longer term"
>
> **FCA research agenda 19/20**

When Google announced a significant advance in quantum computing in October 2019,[1] claiming its quantum computer had completed a task that would take classical computers thousands of years to complete, the phenomenal advance in quantum capability became clear. IBM has further illustrated this progress by consistently showing a doubling in quantum volume, an industry measure of capability, every year since 2017, with a roadmap to continue this doubling through to at least 2023.[2] And new players, such as Honeywell, have delivered similar capabilities and projections for progress. Additionally, there are a large number of quantum computing start-ups and companies with underlying technologies gaining substantial venture capital funding adding to the diversity of approach into the Quantum Computing industry.

2020 has also seen greater commercial access and availability, with Amazon Web Services launching a quantum cloud platform[3] and quantum computer manufacturers offering direct cloud access.

With the quantum computing as a service market expected to grow from $93 million to $283 million by 2024[4], supporting opportunities for savings and revenue growth across industries, it's no surprise that firms including Barclays[5], HSBC[6], NatWest[7] and Caixa[8] have active quantum computing research and development programmes.

This paper therefore seeks to help you in your quantum journey starting by identifying areas of opportunity in financial services to show why you should be excited by quantum computing, focusing on the applications we expect to deliver the biggest early impact: investment, risk, AI and security. Then, we outline the practical steps to start exploiting quantum computing – how to access real quantum hardware through the cloud, how to develop the necessary skills and how to approach building valuable partnerships.

Finally, we provide an overview of what quantum computing is and the different technologies available in a way that focuses on its application within the financial services industry and what makes it different from the computing we use today.

While this paper focuses on quantum computing as an area of particular interest within financial services, there are other quantum technologies profoundly impacting the wider technology world.

For example, PA Consulting has leveraged new quantum accelerometers to demonstrate improved navigation security11, while other quantum-sensing technologies promise more exciting innovations, such as providing hyper-accurate timing devices the size of a matchbox at low cost which could have applications to trade time stamping.

The UK is home to significant quantum technology development, with over £1 billion of investments through the National Quantum Technologies Programme[9] and many leading start-ups and financial services quantum research programmes. This vibrant landscape has given rise to a consortium looking to build the UK's first commercial quantum computer, which consists of Standard Chartered, quantum specialists Rigetti Computing and Edinburgh University, alongside others.[10]

The significance of quantum computing is amplified by the role of data in creating and defining new business models in financial services and across the economy. How firms can use and understand the data they hold will drive enormous efficiencies internally, across back office functions. It will also enable firms to meet consumer needs and create hyper-personalised services. Empowering consumers to share their data as part of an open data economy, where they see a benefit, means new insights and opportunities will be there for those who can understand the data. This combination of new ways of computing and growing data makes this an exciting time in the development of quantum computing, and we're delighted to share our insight into this emerging technology and the opportunities it holds for the UK financial services sector.

WHERE TO FIND THE QUANTUM OPPORTUNITY

Quantum computing is well suited to financial services, with its ability to model a wide variety of options and optimise across those outcomes. However, we are still early in the development of the quantum computer, and particularly quantum programming.

As Bill Gates said, "the computer was born to solve problems that did not exist before," and similarly the quantum computer will have applications and impacts we have not yet conceived of. Nevertheless, there are already a wide variety of applications and impacts we can envisage within financial services across:

- **Investment** – optimising allocation by analysing a greater range of options
- **Risk** – faster and more granular risk assessment
- **AI** – enhancing existing methods to find more accurate or individualised algorithms
- **Security** – a threat to existing standards but also an opportunity for greater security

INVESTMENT

Why is quantum computing exciting for investment?	Where could we apply quantum computing?
In any investment, or allocation of resources, the number of options we want to explore and the possible outcomes for each grow exponentially. That's why today we approximate and run calculations on a periodic or overnight basis. The superposition property of quantum computers will let us consider vast numbers of possible portfolios in real time and with greater granularity.	• **Proactive recalibration** to monitor a market and identify when a better basket of stocks is likely to exist that exceeds transaction cost thresholds. • **Optimise settlement** to more accurately batch transactions, reducing costs. • **Resource allocation** to account for a large number of constraints.

WHAT ARE WE SEEING ALREADY?

Firms are already publicly experimenting with proof of concepts in this space. Barclays is exploring the potential to optimise the settlement of batches of securities transactions[9]. NatWest is demonstrating that calculations around its high-quality liquid assets (HQLAs) portfolio can run 300 times faster than on a traditional computer while providing an even higher degree of accuracy enabling more efficient allocation.[10]

We have also seen published demonstrations from start-ups such as Chicago Quantum[11] who last year successfully used the D-Wave 2000Q system to optimise a portfolio across 60 US stocks in under one minute. The team was able to consistently identify portfolios that are on or ahead of the efficient frontier of portfolios, of which there are more than a quintillion options. Now D-Wave has launched its new Advantage system, with more than double the number of qubits, it will be interesting to see what the team can achieve and whether optimisation that outperforms existing approaches is now within reach.

WHAT SHOULD WE EXPECT NEXT?

Currently, computing capacity is still slightly below the threshold for practical problem sizes, such as optimising across a basket of 500 stocks. But with expected increases in 2021/22, this size of problem might well be in reach soon.

The real advantage for now is unlikely to be a wholescale replacement of your existing investment optimisation method, but rather a hybrid approach where we use a quantum system to enhance or sit alongside the existing system and provide an 'early warning' between recalibrations letting you respond sooner and take advantage of opportunities.

HOW CAN YOU REALISE THE OPPORTUNITY?

Starting with a hybrid approach today might only give you limited advantage. But as the quantum hardware improves exponentially over the next few years, you will be in the perfect position to seize a significant advantage in the near-to medium-term.

Starting with an initial 'proof of concept' hybrid approach using easily accessible cloud platforms today will be an effective way to gain the skills and start to see the near-term advantage in investment analytics.

As the technology matures you will then be well placed to take advantage of the completely new possibilities, such as the real-time bespoke analysis of possible investment options. Quantum computers' ability for parallel processing enables them to move beyond a separate analysis of different investments and instead enables firms to assess multiple options against their risk-adjusted impact on an investment portfolio. This lets you select not just the best option, but the best option for your individual needs based on other holdings.

RISK

Why is quantum computing exciting for risk?	Where could we apply quantum computing?
Risk analytics is incredibly computationally intensive, with many interdependencies across different holdings making the accurate assessment of risk or identification of 'tail events' very difficult. The ability of quantum computers to explore a wider landscape of possible outcomes enables faster, more accurate risk calculations.	• **Monte Carlo simulations** to accelerate risk calculations • **Dependency analysis** to assess and incorporate risk dependencies simultaneously, rather than iteratively • **Individualisation** to consider risks at a more individual level

WHAT ARE WE SEEING ALREADY?

Most major investment banks already have teams looking at the application of quantum computing to risk calculations. Goldman Sachs is focusing on Monte Carlo simulations, a common approach to many risk calculations, and Citi told the Financial Times recently that "the potential for the technology to revolutionise activities like risk management and trading are so great that banks need to start learning how to harness it now".[12]

At this stage, applications are confined to proof of concepts and technology development. HSBC, for example, has recently announced its involvement in the cross-industry NEASQC (Next Applications of Quantum Computing) project to enable the bank to "stay on top of the latest developments, and will be well placed to judge if and when it's the right time to invest in this technology".[13]

WHAT SHOULD WE EXPECT NEXT?

We can expect early applications in areas such as 'early warning' or more individualised risk calculations. For example, using the abilities of superposition to explore many possible outcomes and analyse dependencies between many variables at once, a quantum computer could identify and flag concentration tail risks well before the accuracy is sufficient for regulatory reporting or detailed analysis. This flagging would enable firms to identify risks earlier and run existing computationally intensive calculations to fully assess the risk and react earlier.

HOW CAN YOU REALISE THE OPPORTUNITY?

It's possible today to investigate the impact of quantum computing on risk through extended prototyping running in parallel with existing techniques. Following the lead of many of the investment banks and exploring quantum applications within your risk team, you can build capability to seize the opportunities when they arise. This will put you in the position to get sight of when the degree the advancing quantum computing technology can benefit your business through applying the technology in the real world.

Quantum computing promises to fundamentally transform risk calculations, freeing firms from the need to assess risk on a limited pool, or on an approximate basis, enabling true calculation across a firm's entire holdings. The ability of quantum computeres to perform calculations that consider dependencies simultaneously rather than serially represents a significant change in our ability to calculate risk. Imagine the benefit of being able to see how each option will change the overall risk position, not just for a limited portfolio, or being able to see how an external event will impact all positions, to identify where the greatest risk lies, rather than having to estimate where to focus.

AI

Why is quantum computing exciting for AI?	Where could we apply quantum computing?
The combination of quantum computing and AI, or quantum AI, can substantially increase the accuracy of AI models. A quantum computer can use generative modelling to improve the data set used for training the AI. It can also leverage the property of quantum tunnelling to reduce the risk of optimising around a local solution increasing the chance by 'tunnelling' to better global solutions.	• **Generative modelling** to create test data sets that improve learning of the algorithm • **Hybrid optimisation** to find more accurate and simpler algorithms • **Pattern matching** to find hidden groupings through greater search and analysis capability

WHAT ARE WE SEEING ALREADY?

Standard Chartered is working with the Universities Space Research Association (USRA) to explore quantum applications such as market data generation,[14] investing in the UK's first commercially available quantum computer from Rigetti.[15] It has successfully generated synthetic market data[16] which it sees as having both risk and AI applications that extend into areas such as customer analytics.

In 2017, 1QBit, a quantum software firm, was able to make German credit scoring data publicly available. Running a hybrid approach on both a quantum and classical computer, 1QBit showed equal credit decision accuracy with a smaller number of 'features' or data points.[17]

WHAT SHOULD WE EXPECT NEXT?

As computational capacity becomes accessible, it will be possible to develop algorithms to improve the accuracy or robustness of customer analytics. There is also the potential to apply a quantum algorithm alongside existing methods to provide more individualised recommendations on lending, credit or other financial service products and offerings, as a quantum computer can easily calculate individual dependency impacts.

AI is an area where quantum computing promises to provide a step change in capability, moving from iterative data analysis to a simultaneous approach that can more accurately consider a wider range of data at once.

HOW CAN YOU REALISE THE OPPORTUNITY?

Just as the effective application of AI depends on working with the business to understand the right problems and iteratively improve, quantum AI will require lateral thinking about the types of customer and business problems that could benefit from enhanced AI decision making.

Quantum computing will be a core component of AI as the technology matures – the generative data and modelling capabilities of processing on a quantum computer naturally enhance and enable AI. This, provides a significant boost to the ability of AI to calculate in parallel and explore and assess a wider range of possibilities. Just as the increasing computational power and access to data enabled the expansion and application of today's AI, we can expect the new computational capabilities of quantum computing to open new possibilities.

SECURITY

Why is quantum computing exciting for security?	Where could we apply quantum computing?
Quantum computing is as much a security threat as an opportunity. It simultaneously threatens to end current encryption standards while offering the opportunity to enhance security through Quantum Key Distribution and true random number generation. Firms that consider quantum computing now will be able to lower their cost of change and better take advantage of the new tools available.	• **Replacing existing encryption** as many current standards will become insecure • **Quantum Key Distribution** to provide a provably secure data exchange mechanism • **Random number generation** to seed security algorithms • **Security analysis** to improve monitoring capabilities

WHAT ARE WE SEEING ALREADY?

At Davos 2020, Google CEO Sundar Pichai stated his belief that: "In a five to 10 year timeframe, quantum computing will break encryption as we know it today."[18] And NIST (The US National Institute of Standards and Technology) has already started selecting post-quantum encryption standards, with a target release date of 2022.[19] That's because the ability of quantum computers to quickly analyse large data sets means many of the encryption standards we rely on today, such as RSA, will be easily hackable with a relatively simple quantum computer.

THE THREAT TO FINANCIAL SERVICES

Financial services use these public key encryption standards to secure their online services such as online and mobile banking and transfers. If (and when) a sufficiently powerful quantum computer arrives, these services will be at risk unless post-quantum encryption standards are adopted by the financial services ecosystem. Quantum computers could also enable threat actors to compromise the digital signature algorithms used by websites. This will allow these actors to create fake identities for websites as well as fake updates and downloads. The NCSC offers to "provide additional guidance for those protecting long-lived or highly classified national security information"[20].

As a result, the NCSC (National Cyber Security Centre) identified that in the longer term "quantum computation must be considered as a significant threat when assessing the security of systems that will protect long-lived data".[21]

COUNTERING THE THREAT AND THE SECURITY OPPORTUNITY

While quantum computers represent a threat to existing approaches, they also provide opportunities to enhance security.

A lot of effort is going into addressing the threat from quantum computers. Organisations involved in research include NIST, ISO and ETSI, along with many academics. A number of countermeasures are being explored by this research, namely:

1. Post Quantum Encryption – cryptography that can run on traditional computers and is designed to be proof against cryptanalysis by a quantum computer. NIST makes the point that new algorithms will need to work not only in big computers and smartphones, but also in devices that have limited processor power. It plans to announce post-quantum cryptography standards within the next three years, but has already selected seven finalists as part of this process, so organisations can begin testing/implementing these finalist algorithms now.
2. Quantum Cryptography – cryptographic processes which are performed using quantum technology. Specific uses include random number generation and "quantum key distribution" (QKD), which uses entanglement to create provably perfect secrecy for key exchange where you can actually tell if a key has been intercepted.

Quantum technologies can generate true random numbers which can be used to seed security algorithms or to improve randomness in data sets outside of security. This can be found today in the Samsung Galaxy A Quantum Phone[22] and is available through Cambridge Quantum Computing and IBM.[23]

A small number of financial firms have already applied QKD. For example, a swiss asset manager used QKD to enhance encryption on data transfers to its disaster recovery site[24], China is investing heavily in the technology with banks such as ICBC using QKD over satellite transfer[25], and BT and Toshiba have recently installed the UK's first quantum-secure industrial network.[26]

While very strong security is promised, QKD may not be suitable for communication between the various communicating parties where one does not have access to a quantum computer, for example, in retail card payments.

3. Bolstering existing symmetric cryptography – traditional symmetric cryptography will continue to be assessed for its continued usability against quantum computers.

WHAT SHOULD WE EXPECT NEXT?

The computing technology required to break current encryption standards is likely to arise in this decade, so it's a challenge we must all prepare for.

We need to implement quantum solutions, such as QKD and Quantum Random Number Generation, alongside existing solutions to meet acceptable standards. The NCSC advises that "organisations considering the use of QKD as a key agreement mechanism ensure that robust quantum-safe cryptographic mechanisms for authentication are implemented alongside them".[27] There are also opportunities to use the same computing advantages in AI and risk analysis to enhance network and security monitoring.

HOW CAN YOU REALISE THE OPPORTUNITY?

Keeping up to date with the development of new standards and the progression of quantum technology will help you consider and plan for risks and future changes across your organisation. Quantum will be particularly important to consider for very long term and sensitive data arrangements.

Firms can also test today's commercial quantum technologies for QKD and random number generation alongside existing approaches. This could enhance current security and set you up for the transition to a fully quantum-secure approach.

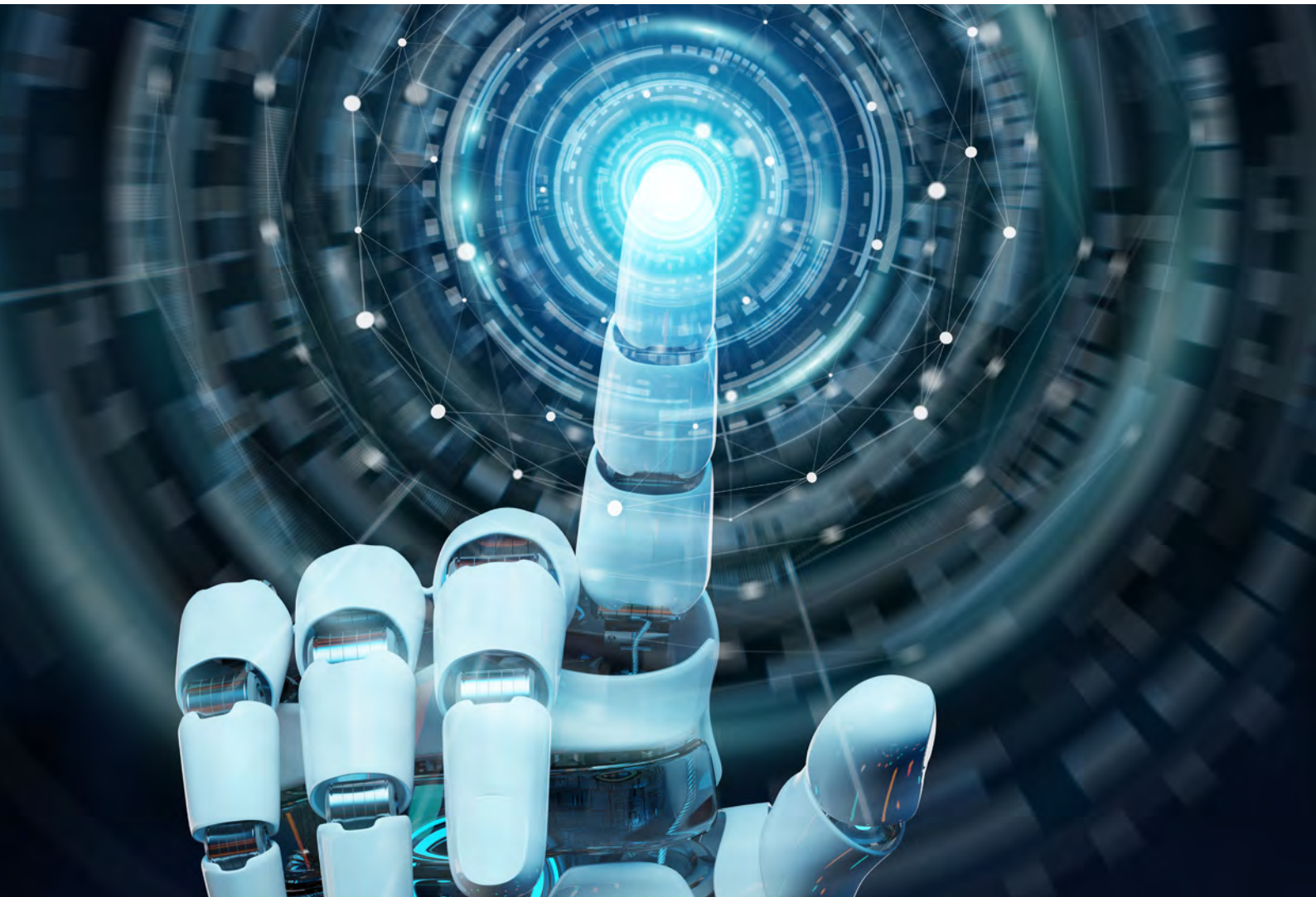
Quantum computing represents a fundamental change in our security arrangements, providing both opportunities and threats equivalent to the introduction of public key cryptography or use of cloud infrastructure. This is a technology that security leaders need to be aware of and consider in their plans.

HOW TO SEIZE THE QUANTUM OPPORTUNITY

As evidenced, quantum computing is likely to have a significant impact across the financial service industry, with many firms already exploring the technology, investing in skills and developing partnerships to ensure they are prepared. Joining them will ensure you can capitalise as quantum technology matures.

You will need to explore how to access quantum computers, the capabilities your firm will need and how you can work with others to maximise value. In this chapter, we explore these three key areas through:

- **Cloud**
- **Skills**
- **Partnerships**



CLOUD

Accessing real quantum hardware is possible today, and easier than you might expect. You can purchase time on a cloud-accessible computer right now at similar prices to classical cloud computing, either by contacting hardware providers directly, such as IBM or Rigetti, or using your existing cloud platform provider's quantum computing service, such as AWS Braket or Azure Quantum.

It's even possible to buy a quantum computer for your sole private use. The upfront cost is approximately $15 million[28] and the technology is at an early stage. However, this may be appropriate where commercial advantage, data confidentiality and/or security concerns and usage demand are significant.

HARDWARE PROVIDERS

The likes of IBM, Rigetti and D-Wave have offered access to their quantum computers for a few years, and Google has announced that it will offer a quantum computing service. Typically, this is through a cloud-access environment connected to several cloud-linked quantum computers.

In the past, you will have had to pre-process your calculation locally and send a mathematical problem, set out in a quantum form (as a quantum circuit), directly to the computer. Now, we are seeing more 'hybrid solvers', which provide a standard set of problem types to enable a more intuitive definition of the problem as the writing to the quantum computer is predefined. This approach allows you to set out a standard problem such as finding the minimum path between two points and instead of you having to translate this into the mapping problem that is written onto the quantum circuit, you can simply provide the locations and paths which are then translated and optimised using a standard approach.

CLOUD PLATFORM PROVIDERS

Last year, Amazon launched its Braket service and Microsoft has launched an Azure Quantum service. With these platforms, you have access to a variety of hardware providers on a pay as needed basis, which could be advantageous as the different quantum computer makers advance at different rates and in different directions and the platforms therefore provide access to a choice of platforms to match the opportunity.

CURRENT ACCESS CARRIES SECURITY CONCERNS

It's important to note that regardless of the provisioning approach, a key difference between quantum and classical cloud access is that you are using the same small number of computers as your competitors. You can reduce the risk by only sending the mathematical calculation data the quantum processor needs, but this could still raise confidentiality concerns over data.

Cloud access makes the arrival of quantum computers very different to the implementation of classical computers in the 20th century. Upfront investments focus on resource and skills, rather than the technology itself. Your team could also run calculations on real hardware within hours, without the need for complex implementation and integration.

SKILLS

Skills are likely to remain a limiting factor for many firms as they explore quantum technologies. You need people with both the technical skills and an understanding of the business problems to unlock value from quantum computers.

TRAINING AND RECRUITMENT

One key challenge firms face is that there are not many people with the combination of quantum computing skills and the understanding of financial services required to identify and solve problems with immediate relevance to firms today. We also see that much of the university focus to date has been on the building of quantum computers rather than their programming, even though traditional programming approaches are quite different to quantum ones.

Therefore, it is likely firms with strong traditional technical capabilities that focus on upskilling their people will have a significant advantage in the development of quantum solutions.

As quantum computing develops further, it's likely that more programming focused courses and certifications will emerge from technology firms such as IBM[29] and Microsoft[30].

COMPLIANCE AND OVERSIGHT

As quantum computing is different from classical computing, there are new risk and compliance considerations. You should ensure your compliance capability is aware of the technology and has considered the risks involved. Two key areas are:

- **Data transfer**
  Data transferred to cloud quantum computers through hardware providers won't be within your security arrangements. So, it's important to anonymise data to avoid the risk of malicious breaches.
- **AI and model ethics**
  Quantum computers can accentuate the challenge of understanding how a decisioning algorithm works as they identify solutions rather than iteratively calculate them. So, it will be even more important for your team to understand how the calculations run so they can watch for systemic bias or unforeseen data artefacts creating unobserved risks.

There are also opportunities to improve compliance by leveraging the ability of a quantum computer to compute across outcomes and analyse dependencies. This could enhance trade monitoring, early risk warnings, network analysis for financial crime or trade compliance analysis.

PARTNERSHIPS

As we've seen with other emerging financial technologies, partnerships will be a key part of quantum computing, especially as financial service firms are exploring the applications of this early-stage technology.

HARDWARE PROVIDERS

Many of the providers already mentioned encourage community collaboration across their platforms, allowing firms with similar problems from different industries to work together and share the development burden. IBM's Q Network, for example, brings together large firms and software start-ups to explore potential applications together.[31]

START-UPS

There's a growing software ecosystem that includes specialist financial services quantum computing firms. For example, 1Qbit, a quantum software start-up based in Canada, worked closely with CME Group to develop a Market Sentiment Meter that improves risk management.[32]

UNIVERSITIES

Quantum computing is an area of significant academic research. As businesses strive to find uses for the technology emerging from universities, many are looking to third-party specialists to bridge the gap between business and academia. That's because it often takes a diverse group to turn academic theory into business practice.

GOVERNMENT

There's strong government investment into quantum computing, with grants available to both academic and private institutions exploring the technology. There are many investments here in the UK, including the Industrial Strategy Challenge Fund, which is investing £153 million alongside £205 million from industry.[33] These opportunities are being taken up by financial services firms through public-private partnerships, which involve a mix of government and private sector funding to grow the technology in a mutually beneficial way.

WHAT IS QUANTUM COMPUTING?

Understanding quantum computing is a challenge as it relies on exploiting quantum mechanics. And as Richard Feynman, a father of quantum computing, said "nobody understands quantum mechanics". This and other comments have created an unhelpful mystique around the word "quantum". It's a label for a set of physical principles first discovered nearly a century ago – an understanding of which has deepened over the decades. Over the last 20 years,materials technologies and techniques have developed to the point where commercial benefit is possible.

To reap this benefit, a general understanding of what quantum computing is and is not, certain aspects of how it works, and how it is likely to develop will enable you to effectively focus on the right opportunities, challenges and risks, enabling value to be realised from this emerging technology more quickly.

A FUNDAMENTALLY DIFFERENT COMPUTER

The world we experience in our everyday is one of 'classical physics', of Newton's apple falling in a predictable and observable way. The classical computers we use in our everyday are part of this world of cause and effect, leveraging technology to create predictable bits of 1s and 0s in which we can write a problem, manipulate them and observe our calculations and solutions.

At its fundamental physics level, the quantum world is very different from our everyday. It's a strange, unpredictable and unobservable world. Quantum computers use technology to actively seek this world, creating 'qubits' (quantum bits) that are 1s, 0s or both at the same time, and that we cannot observe or measure without destroying their quantum nature.

It's a mistake to try and understand the quantum world through our everyday expectations. As Werner Heisenberg said: "Not only is the universe stranger than we think, it is stranger than we can think." The good news is that the application of these principles to practical effect is understood by a fast-growing number of quantum computer programmers, physicists and engineers and it is a very popular subject at undergraduate and postgraduate level. Taking this quantum view enables you to move beyond thinking of quantum computers as simply faster and better classical computers. Instead, consider quantum computers as a new kind of computer trying to solve different problems in a different way – computers that are better suited to probabilistic, rather than deterministic, problems.

HOW QUANTUM COMPUTATION WORKS

There are three key quantum properties that quantum computers aim to exploit: superposition, entanglement and interference. These are explored in the table below, which compares these principles with their classical analogues.

Introducing these properties moves a quantum computer away from a deterministic step by step calculation into a probabilistic world that creates significant acceleration in statistical problems. Below we outline in more depth how each of these properties is different from those we use in a classical computer and what they mean for the types of calculation we perform.

Quantum Computation

Superposition

Qubits store and process information as 1s or 0s or a combination of both at the same time – the superposition state.

A superposition of values is written onto each qubit:

1/0 ... **1/0 1/0 1/0**

The variable is any combination of 2n values for each calculation, such as:

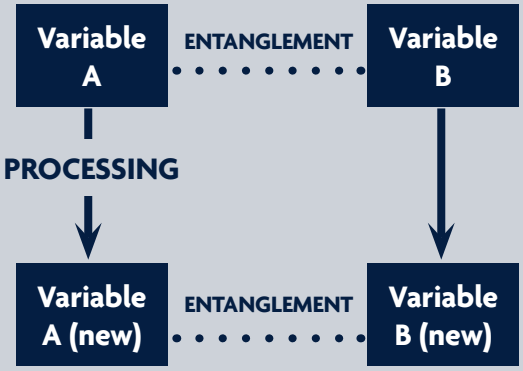
all even numbers OR **12, 784, 5,783...**

This 'superposition' of multiple values (or states) means we can input and run a computation on all possible values a variable could take at once.

For example: calculating all possible stock returns.

Entanglement

The value of each qubit can depend on, and effect, other qubits. So, by processing one variable, you affect other 'entangled' variables.



This dependence allows us to write the relationship between variables directly into the computer and include this directly into calculations.

For example: calculating the possible returns of correlated stocks.

Classical Computation

Certainty

Binary bits store and process information as 1s and 0s, and error correction technology ensures these bits remain in their expected state.

A specific value is written onto each bit:

1 ... **1 1 0**

The variable is one of 2n values for each calculation, such as:

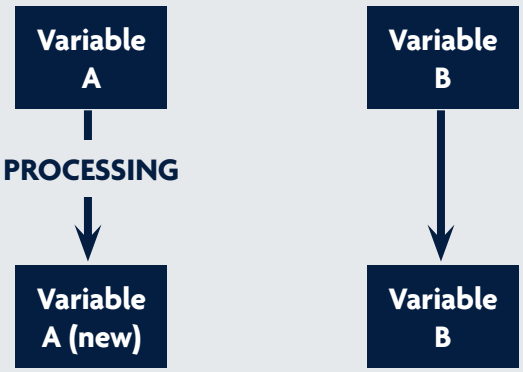
256 OR **1,387**

This certainty allows us to input a variable into a computation, know its value at each stage and get a consistent expected solution.

For example: calculating a stock's actual return.

Independence

The value of each bit is independent of every other bit. So, when you perform a calculation on one variable, there's no impact on other variables.

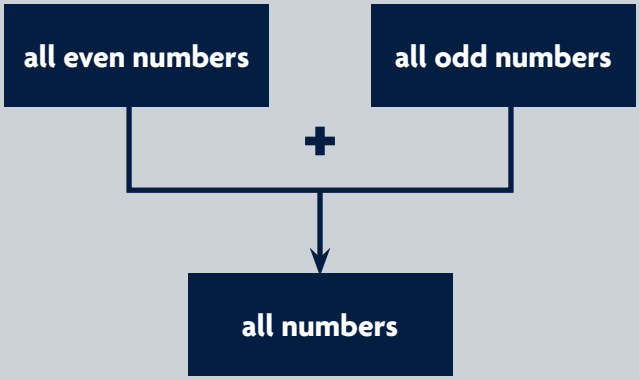


This independence allows us to perform separate calculations on independent variables.

For example: calculating the actual returns of different stocks.

Interference

Combining variables in different qubits means combining their complex probability wavefunctions, this is like vector algebra.

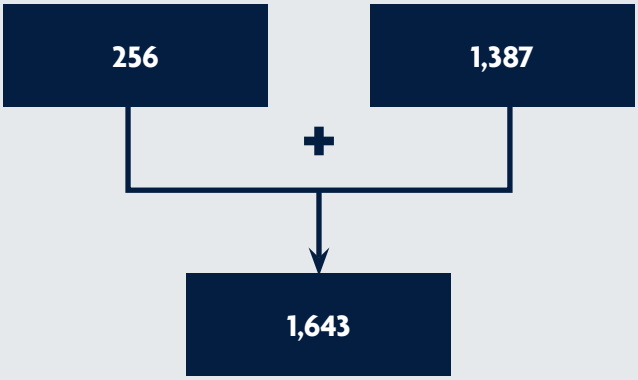


This ability to combine the probability vectors of different variables allows us to directly combine probabilities without having to break them down and assess each combination individually.

For example: finding the greatest total returns across a set of stocks for a variety of scenarios in a single calculation.

(Scalar) Combination

Combining variables stored in different bits means combining positive and negative values.



This ability to combine numbers in a 'scalar' way allows us to break down and perform complex mathematical calculations.

For example: calculating and combining total returns across different stocks.

These different properties of a quantum computer lead to a very different approach to computation and programming. Classical programming is about breaking down a problem into a series of iterative steps and then running through these steps typically as quickly as possible. In contrast, quantum programming is about expressing a problem as a set of functions that together can be mapped onto a quantum computer and carried out in one step or a small number of steps.

Both quantum and classical computing have benefits and limitations, so are suitable for different types of problem. We should therefore think in terms of hybrid solutions, breaking down problems into classical and quantum parts, and using the best computational approach in each case.

In the chapter *Where to find the quantum opportunity*, we explored examples of valuable problems in different areas of finance, showing how you can introduce quantum computation to enhance and improve your existing approaches.

QUANTUM HARDWARE

As well as computing in a different way to a classical computer, the hardware of a quantum computer is very different. It takes innovative technology to enter the quantum realm and exploit quantum mechanics for computation but there are lots of exciting technology firms engaged in solving this challenge. While members of the financial services sector are more likely to focus on the applications and programming of a quantum computer, there are terms you might here and differences between platforms that are useful to appreciate.

SUPERCONDUCTING QUBITS

Many of the advanced quantum computers discussed in the media today, including the likes of Google, IBM and Rigetti, use superconducting electronic circuits. These circuits consist of superconducting loops, with each loop representing a qubit, just as each transistor represents a bit on a classical computer. A microwave radio sets the state of each qubit and performs calculations.

The quantum processing chip itself is very small and could fit in the palm of your hand. However, the chip needs cooling to just above absolute zero, so most of what you see in pictures is the very large dilution refrigerator needed to achieve this.

ION TRAPS

Instead of creating qubits using superconducting loops, ion trap computers such as IonQs use single atoms, which are naturally quantum. They trap each atom to keep it separate from its neighbours, and use lasers to control its value and move it around to interact with other atoms.

QUANTUM ANNEALERS

While superconducting qubit and ion trap computers are like a CPU, able to address any qubit throughout a calculation, an annealer can only set up and perform a single type of calculation – finding the global minima of a system. This limit in flexibility means annealers aren't true 'Turing' computers.

That's why quantum annealing computers such as those provided by D-Wavealso use interconnected superconducting qubits. The value of each qubit can be set at the start of a calculation and the chip will settle in the lowest possible energy configuration. Many of the calculations we might want to run, for example, finding the optimum stock portfolio, can be set up as an annealing problem.

In the chapter *How to seize the quantum opportunity*, we explored the different ways to access these computers, including through the cloud, and how skills and partnerships can help you get the most out of your access.

POST WORD

Quantum computing is an exciting field. and we have been delighted to share our insight into the technology, how we expect it to transform financial services and what you can do to make the most of the opportunity.

As you can see quantum computing will have applications across financial services, transforming the way we approach investment, risk, AI and security and offering financial services firms that seize the opportunities an early advantage.

Financial services firms should be considering how they prepare for the quantum computing technology that looks certain to transform the market. Failing to do so risks others developing the ability to move faster in the short term and to attract the resources that will be essential for long-term success.

The challenge will be in combining scarce quantum technology skills with deep knowledge of the obstacles surrounding financial services to quickly realise value from new initiatives. While it won't be easy to overcome this challenge, doing so will unlock immense opportunity.

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