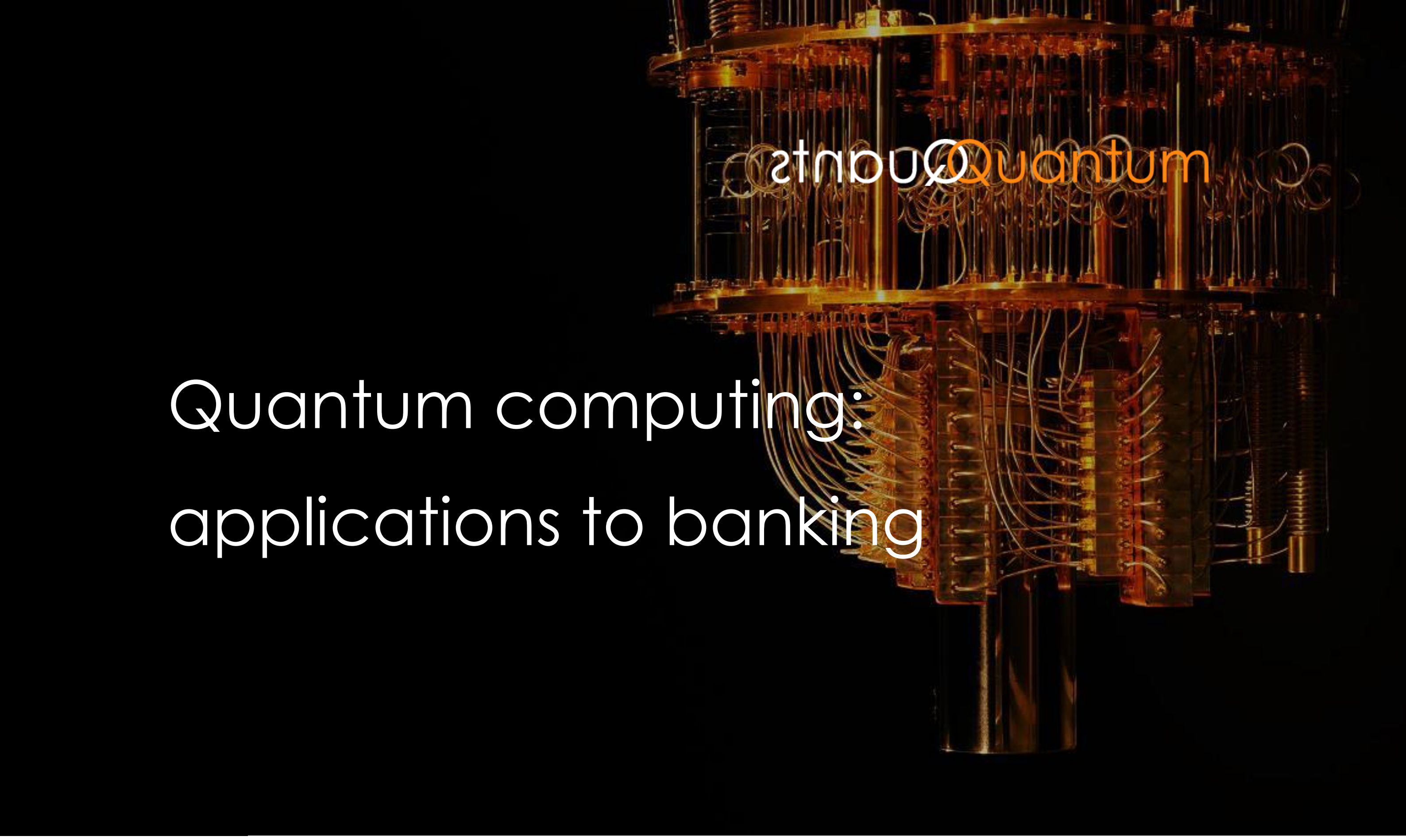

Quantum computing: applications to banking

Many financial institutions are currently investigating the possibilities of benefiting (and securing themselves) from the quantum leap, i.e. the advent of quantum computation on a large scale.

Portfolio optimization, Monte Carlo simulations and pricing derivatives are only few of the many applications for which a quantum computer will outperform even the fastest supercomputers in the financial industry.

This article presents an overview of the applications of quantum computing to banking.

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Quantum mechanics, superposition and entanglement

Quantum mechanics is the theory that describes the dynamics of microscopic particles [1] [2]. Such particles behave differently from what we are used to see in the classical macroscopic world in which we live. In certain conditions these microscopic particles (e.g. electrons or photons) behave like waves. This means that quantum particles are not described by single points or hard objects, as it happens for classical objects, but they are described by probability distributions. Quantum mechanics is the theory that defines the evolution of the probability distribution of a (system of) microscopic particle(s).

This probabilistic nature of quantum particles leads to two non-classical phenomena which are the basis of quantum computation: superposition and entanglement.

Superposition is the simultaneous existence of a particle in multiple states. A quantum particle can be simultaneously "dead" or "alive", "0" or "1", "on" or "off".

Entanglement is the state of perfect correlation between two particles, for which a measurement on one of the two leads instantaneously to the change of the state of the other particle.

In the following we describe the idea behind quantum computing and the applications of quantum computing to the financial industry.

Quantum computing: a new paradigm?

Calculations on a classical computer are based on the binary system, where the information is carried by bits assuming value 0 **or** 1.

On a quantum computer [3] [4], i.e. a computer which processes information using quantum particles, the smallest unit of information is the quantum bit (or qubit). The qubit is the state of a quantum particle, which due to the superposition property of quantum particles can simultaneously assume value 0 **and** 1. More specifically a qubit can assume a value of any linear combination[1] of 0 and 1.

This feature, together with the entanglement between qubits, makes a quantum computer capable of data intensive applications and calculations which would be hard to perform on a classical computer. As an example, k qubits can potentially represent 2^k bits of information. Further, certain functions on quantum qubits (quantum operators or gates) can be used to: finding patterns and correlations that point toward a solution (Grover algorithm [5]), exchange a key in a "super-secure" way (BB84 protocol [6]), exponentially speed up classical operations (Quantum Fourier Transform [7]), etc.

On the other hand, there are calculations which are easy to perform on a classical computer that are currently more expensive on a quantum computer (e.g. scientific computing, term-to-term product, etc.).

This suggests that the applications of quantum computers in the near future will be based on hybrid architectures, in which the advantages of quantum calculations are embedded in a classical framework.

Quantum banking

The financial industry is constantly searching for new technologies that can leverage higher performances and profits. For instance, the progress in the fields of data science and artificial intelligence is an example of how financial services have been and are currently benefiting of new technologies to explore business models and markets which could previously not even be imagined.

Quantum computing is presently being investigated by several big players in the financial industry [8] [9] [10] to be

[1] The coefficients of this linear combination need to be such that the sum of their squares equals 1.

ready for the quantum leap, i.e. the moment in which the quantum computers will be available on large scale for practical applications.

Most of investigation is focused on data-intensive applications (big data), optimization problems, simulations and modelling [11] [12].

Besides the experimental research on the construction of a stable quantum computer, from a theoretical point of view the research is based on determining quantum algorithms (i.e. algorithms on a quantum computer architecture) which present an advantage in terms of input capabilities or speed with respect to a classical computer.

Several optimization algorithms have been developed for quantum computers, i.e. quantum optimization algorithms. Portfolio optimization is an NP-hard (non-deterministic polynomial time-hard) problem, that is it is very difficult for classical computers to efficiently determine the best portfolio composition. In particular, quantum annealing is a promising quantum optimization algorithm. This algorithm finds the global minimum of a function by using quantum fluctuation to investigate the space of possible solutions. Google published a result in 2016 that seems showing how quantum annealing outperforms the classical simulated annealing by a factor of 10^8 [13].

From a banking perspective, the models used to determine the price (or value) of a financial instrument or portfolio only include some of the drivers needed to describe the dynamics of the value. The optimization of a portfolio becomes in fact more and more complex and time consuming when the number of instruments, drivers and targets grows. Tasks like multi-objective optimization are expected to speed-up the performance of the algorithms when implemented on a quantum computer.

Besides optimization, another methodology extensively used in finance is simulation (Monte Carlo). For instance, a stochastic approach can be used to simulate the effect of uncertainties around the drivers of the price of a financial derivative or obtain the credit exposure of a risky portfolio. On a classical computer, the precision of the simulation depends on the number of simulations. On the other hand, several quantum algorithms have been constructed to perform simulations on a quantum computer. The most promising algorithms are extensions of the amplitude estimation and amplification method used in the Grover's search algorithm [14]. It has been shown that these types of algorithms provide a quadratic speed-up compared to their classical counterparty [15]. Applications to finance in this regard have been proposed [16] [17].

Another field that is currently at the center of investigation of the financial industry is data science, and more specifically machine learning. In particular, neural network models have been proven successful in analyzing credit risks, predicting market forecasts, fraud detection, trading, etc.

Training a machine learning model corresponds roughly to find the solution to a large system of equations, which is also equivalent to diagonalize a large matrix. In 2009 Harrow, Hassidim and Lloyd introduced a quantum algorithm (the HHL algorithm) [18] to solve linear system of equations on a quantum computer. This algorithm shows an exponential improvement relative to the best classical algorithms, therefore it has been extended since then to create many other variants of quantum machine learning algorithms. Few famous examples are quantum principal component analysis (QPCA) [19], quantum support vector machine [20] and quantum machine learning [21] [22].

Besides these applications, researchers are currently looking at possible applications of quantum computing to banking from many other points of view. We close this section with an honorable mention of these applications: security. Cryptography is in fact another key application to the banking industry. Currently (almost) all encryption systems rely on the difficulty of breaking down large numbers into prime factors. For classical computers this calculation is generally very slow and this ensure the security of this system. However, on a quantum computer, the Shor's algorithm [23] provides an exponential speed-up compared classical algorithms. When a sufficiently powerful quantum computer will be built, if no alternative to our security system is found, our data might not be safe.

Waiting for the quantum leap

Google, IBM, Microsoft, Honeywell, and many other companies are currently investing a lot of resources in the run to "quantum supremacy". The results from this run give us mainly three suggestions: 1. quantum computing works, 2. it can be faster than classical computers and 3. it seems to open many doors to new applications.

However, there are still many challenges to be faced before quantum computing will break through a large scale usage. In particular, state preparation (input) and decoherence are two of the main challenges which slow down the progress and the possible testing of many algorithms. In fact, there is no efficient way yet to prepare the qubit states in a given configuration, e.g. to represent a time series. Several ideas have been proposed, among which the qRAM [24] is a promising way which would allow the implementation of many of the existing quantum machine learning algorithms. Decoherence is instead a consequence of the quantum particles which constitute the quantum computer interacting with the environment (including the computer itself and the measurement devices), leading to noise and loss of information from the quantum computer into the environment. For this reason, a lot of research is focused on the so-called error correction algorithms, to avoid loss and restoring quantum information.

A lot of attention is therefore out there on quantum computing and its possible applications. Finance, banking and data science will be boosted once the quantum supremacy is reached. It is therefore the best time to understand the challenges and to catch the opportunities that quantum computing is unveiling.

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About Quantum Quants

Quantum Quants helps companies to get insights on applications of quantum computing to the financial industry and data science.

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