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The impact of Quantum Computing on business models: possible scenarios

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Glossary[1]

Quantum physics: physical theory developed to describe phenomena that occur at the microscopic level on the atomic and subatomic scale, in which many of the equations of classical mechanics are inadequate. In classical physics, objects exist in a specific place at a specific time. Instead, in quantum physics, objects exist in a fog of probability; they have a certain probability of being in point A, another probability of being in point B, and so on (Coolman, 2014).

Quantum mechanics: term coined by Niels Bohr, Werner Heisenberg, Erwin Schrödinger, and other physicians in 1920s (Wikipedia, n.d.). It is defined as the mathematical framework at the base of quantum physics. «It characterises simple things such as how the position or momentum of a single particle or group of few particles changes over time» (Webb, n.d.).

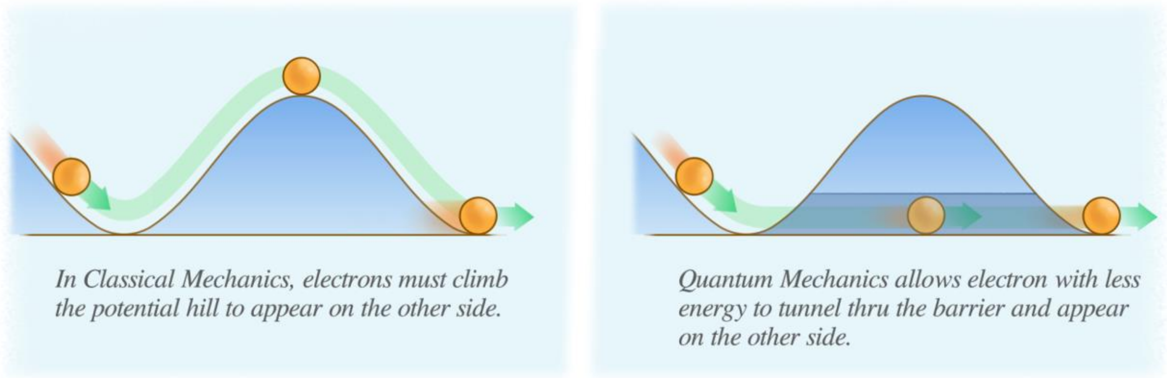
Wave function (in quantum mechanics): «variable quantity that mathematically describes the wave characteristics of a particle. The value of the wave function of a particle at a given point of space and time is related to the likelihood of the particle's being there at the time» (Britannica, n.d.).

Superposition: principle of quantum mechanics according to which a quantum particle can be in several states at the same time. For example, the rotation of an electron in a magnetic field can be a random combination of "up" and "down", until it is measured, and a single direction of movement is identified; as opposed to a coin, which we know to be heads or tails, not in a combined state of the two (jqi, n.d.).

Entanglement: principle of quantum mechanics that occurs when two or more quantum particles (e.g., photons or electrons) enter a state that cannot be described exclusively by the states of the individual particles; the particles form a unified system for which measuring the state of one particle instantly provides information about the state of the other, even if the two particles are not close to each other (Sutter, 2021).

[1] Definitions are a personal elaboration based on literature and experts' voices during the research at Observatory Quantum Technologies - Politecnico of Milan.

Tunnelling: «phenomenon in which particles penetrate a potential energy barrier with a height greater than the total energy of the particles. The phenomenon is interesting and important because it violates the principles of classical mechanics. Quantum tunneling is important in models of the Sun and has a wide range of applications, such as the scanning tunnelling microscope and the tunnel diode» (Kramer, 2020).



”Contrasting classical (over the barrier) motion vs. quantum (through the barrier) motion.”[2]

Quantum technologies: class of technologies whose operation is based on the design and active manipulation of quantum states of matter, exploiting the principles of quantum mechanics. Quantum technologies can be divided into four application areas: Quantum Computing, Quantum Simulation, Quantum Communication, Quantum Sensing & Metrology (Quantum Flagship, n.d.).

Quantum Information Science (QIS): emerging field pertaining to science and engineering involving computation, communication, precision measurement and fundamental quantum science. The roots of this field date back to the 1980s, when pioneers such as Charles Bennett, Paul Benioff, Richard Feynman, and others began to think about the implications of combining quantum mechanics with the classical Turing computer machine (U.S Department of Energy, n.d.).

HPC (High-performance computing): «use of parallel processing for running advanced application programs efficiently, reliably and quickly. The term applies especially to

[2] Source: https://chem.libretexts.org/Courses/University_of_California_Davis/UCD_Chem_107B%3A_Physical_Chemistry_for_Life_Scientists/Chapters/4%3A_Quantum_Theory/4.09%3A_Quantum-Mechanical_Tunneling

systems that function above a teraflop or 1012 floating-point operations per second. The term HPC is occasionally used as a synonym for supercomputing, although technically a supercomputer is a system that performs at or near the currently highest operational rate for computers. Some supercomputers work at more than a petaflop or 1015 floating-point operations per second» (Awati, n.d.).

Moore’s Law: «Moore's law is a term used to refer to the observation made by Gordon Moore in 1965 that the number of transistors in a dense integrated circuit (IC) doubles about every two years» (Gianfagna, 2021).

Quantum Computing: computational systems based on quantum bits (qubits) that exploit the principles of superposition and entanglement of quantum mechanics to overcome the binary logic of traditional computation, in which a bit can have a value of 0 or 1. A qubit can take a value of 0, 1 or a combination of 0 and 1, moving from a deterministic to a probabilistic measure. In this way, the system can process multiple inputs at the same time reducing the number of operations required to obtain the result. If the classical computer can perform n operations with n bits, a quantum computer with n qubits can perform 2^n and therefore can be 2^n times faster (Marchenkova, 2016).

Qubit (or quantum bit): unit of measurement of information in quantum computing, that is the quantum analog of a classical bit (Quantum Inspire, n.d.).

Superfluids: «an unusual state of matter noted only in liquid helium cooled to near absolute zero and characterized by apparently frictionless flow» (Merriam Webster, n.d.). Superfluid helium is used in quantum computing hardware to trap electrons in vacuum above the surface (Swayne, TQD Exclusive: Steve Lyon, Nick Farina Discuss EeroQ’s Long-term Vision, 2021).

Quantum Speedup: it can be talked about speedup when the quantum computer performs better than a classic computer for a specific problem. The speedup is classified according to how much the quantum computer is able to scale in terms of resolution time as the size of the problem increases (Quantum Computing Scaling). It can be talked about demonstrable quantum algorithms when there is a mathematical proof of speedup compared to the classical algorithm; about heuristic quantum algorithms as the speedup is intuitive but not mathematically demonstrable and it therefore becomes necessary to compare the performances obtained on classic hardware (Limited Quantum Speedup) (Rønnow T. F., 2014).

Quantum Advantage: situation where a quantum computer can perform a particular computation significantly faster than the best classical computer (techopedia, n.d.).

Quantum Supremacy: situation in which a quantum computer is able to calculate a solution to a particular problem that no classical computer can solve, at least not in a reasonable amount of time (Brown, n.d.).

Quantum Error Correction: «set of methods to protect quantum information—that is, quantum states—from unwanted environmental interactions (decoherence) and other forms of noise» (Brun, 2020). The quantum error correction is an important concept because help to understand the difference between *logical and physical qubits*. «Because quantum computing requires us to encode information in qubits, most quantum algorithms developed over the past few decades have assumed that these qubits are perfect. They can be prepared in any state we desire and be manipulated with complete precision. Qubits that obey these assumptions are often known as *logical qubits*. The last few decades have also seen great advances in finding physical systems that behave as qubits, with better quality qubits being developed all the time. However, the imperfections can never be removed entirely. These qubits will always be much too imprecise to serve directly as logical qubits. Instead, we refer to them as *physical qubits*. In the current era of quantum computing, we seek to use physical qubits despite their imperfections, by designing custom algorithms and using error mitigation effects. For the future era of fault-tolerance, however, we must find ways to build logical qubits from physical qubits. This will be done through the process of quantum error correction, in which logical qubits are encoded in a large number of physical qubits» (The Jupiter Book Community, n.d.).

Gate Model Quantum Computer (Universal Quantum Computer): general-purpose Quantum Computing architecture, for which quantum supremacy has been demonstrated to date from a theoretical point of view. The structure is defined by operations on quantum circuits, similar to the operations of classical computers, which can be put together to create any sequence of calculations, performing increasingly complex algorithms. There are different types of qubits studied for the construction of this type of quantum computer: superconducting, topological, photonic, ion-trapped, cold atoms, laser optics (Singh, 2021).

Quantum circuits: model for quantum computing, in which the steps to solve the problem are quantum gates performed on one or more qubits. A quantum gate is an operation applied to a qubit that changes the quantum state of the qubit. Quantum gates can be divided into single-qubit gates and two-qubit gates, depending on the number of qubits on which they are applied simultaneously (it is also possible to define three-qubit gates and other multi-qubit gates). The quantum circuit ends with a measurement of one or more qubits (Quantum Inspired, n.d.).

Quantum Annealer: special-purpose Quantum Computing architecture for optimization problems, for which quantum supremacy has not been demonstrated from a theoretical point of view but can be researched heuristically. If in the Gate Model the problems to be solved are expressed in terms of quantum gates that can express any type of problem by modifying the algorithms, in the annealer architecture it is necessary to reformulate the problem in such a way that the interactions of the qubits represent the specific problem. wants to solve. This means encoding the interactions between qubits and weighting each qubit to specify the problem and constraints. This type of architecture allows the resolution of some optimization problems: in the search for the best combinations to solve the problem, the physical principle is exploited (also valid in the quantum world) for which everything tends to a minimum energy state. The Quantum Annealer simply uses quantum physics to find the low-energy states of a problem and thus the optimal or near-optimal combination of elements (DWave, n.d.).

Quantum Algorithms: Algorithms designed to run on a quantum computer with the aim of achieving a speedup, or other improvement in efficiency, over a classical algorithm. The theory of quantum algorithms has been an active research area since the 1990s, even prior to the first practical experiments on quantum hardware (Quantum Inspired, n.d.).

Shor’s algorithm: «quantum algorithm for factoring a number N in O((logN)3) time and O(logN) space, named after Peter Shor. The algorithm is significant because it implies that public key cryptography might be easily broken, given a sufficiently large quantum computer» (Quantiki, n.d.).

Grover’s algorithm: quantum algorithm that resolves the problem of searching in a database through unstructured data. After Shor’s algorithm, it’s the most important algorithm in quantum computing (Nikhade, 2021).

Loss of coherence (quantum decoherence): it means that the quantum computer loses the ability to maintain the superposition of states, whereby the system collapses in one state or another, apparently becoming classical and losing quantum information. The loss of coherence can be caused by vibrations, temperature fluctuations, electromagnetic waves, impurities in the qubit material and other interactions with the external environment that destroy the quantum properties of the computer, lowering its useful life and generating errors (techopedia, n.d.).

Fault tolerance: it is the ability of a quantum computer to remain so, that is, to carry out a quantum computation in a reliable way, for all the time necessary for the execution of the calculation, keeping the probability of error below a certain critical value. A system can be designed to ensure hardware-level fault tolerance and be equipped with error correction systems (Grassl & Rötteler, 2009).

NISQ Computer (Noisy Intermediate-Scale Quantum Computer): term coined by physicist John Preskill to define the types of quantum computers that will be available in the coming years. “Noisy” refers to the fact that devices are disturbed by what is happening in their environment. For example, small changes in temperature, stray electric or magnetic fields can cause the quantum information in the computer to degrade. "Intermediate Scale" refers to the fact that the number of qubits will most likely be limited to a few hundred or a few thousand (Ackermann, 2018).

Quantum Communication: communication networks based on quantum physics principles. In quantum communication, the entanglement principle plays an important role: qubits can be intertwined, allowing the quantum states of particles to be correlated over large distances (Quantum Delta Nederland, 2019). Another property of qubits is that they cannot be copied with an identical superposition. Consequently, any attempt to intercept, read, and forward a qubit-based communication is traceable by comparing the states of received qubits with the states of sent qubits. Quantum communication is therefore potentially immune to external interference, provided that the sender and receiver can reliably identify each other. This paves the way for the exchange and processing of data in a fundamentally secure manner. However, the long-distance transmission of qubits is not straightforward. To address this problem, efforts are being made to develop special quantum repeaters (Quantum Delta Nederland, 2019).

Quantum Internet: «a network that will let quantum devices exchange some information within an environment that harnesses the weird laws of quantum mechanics. In theory, this would lend the quantum internet unprecedented capabilities that are impossible to carry out with today's web applications» (Leprince-Ringuet, 2020). A quantum internet would be to transmit large volumes of data over immense distances at the speed of light.

Quantum Cryptography: involves the design of cryptographic solutions that exploit the principles of quantum physics to ensure greater security, e.g., QKD (QuantumXChange, n.d.).

Post-Quantum Cryptography: design of cryptographic solutions that can be used on classical computers but resistant to the potential attack by a quantum computer (QuantumXChange, n.d.).

RSA algorithm: «RSA algorithm is asymmetric cryptography algorithm. Asymmetric means that it works on two different keys i.e., Public Key and Private Key. As the name describes that the Public Key is given to everyone, and Private key is kept private» (GeeksforGeeks, 2021).

Quantum Simulation: type of approach to quantum computation whose goal is to solve complex quantum problems by mapping them on analog or digitally controlled systems. Compared to Quantum Computing, simulations are specialized and require neither universality nor fault-tolerance, thus allowing faster and more efficient scaling using specialized quantum software (Quantum Delta Nederland, 2019).

Quantum Sensing & Metrology: quantum sensors are tools capable of observing changes in the environment, such as changes in temperature, radiation, acceleration, time (clocks), and electric or magnetic fields. Unlike classical sensors, quantum sensors rely on quantum phenomena, such as entanglement, to detect variations (Quantum Delta Nederland, 2019). Quantum sensors are extremely sensitive and therefore allow for more precise measurements. They are also capable of extremely high resolution, which means that tiny structures such as DNA can be measured. Quantum Metrology uses quantum sensors to define standards, e.g., time measurement or electrical measurements (Quantum Delta Nederland, 2019).

Introduction

Every individual makes choices. Often, if not always, there is only one way to follow among two or more, since it is slightly impossible to take the two "ways" and be present at the same time in both. An individual chooses one path, another one or others, but still only one can be followed.

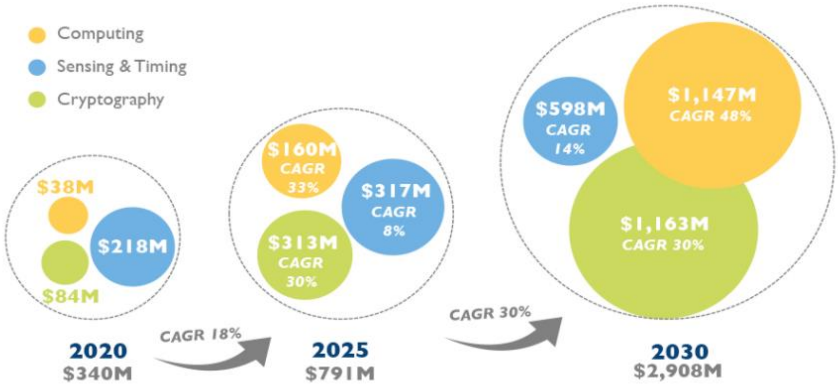
All this is reasonable in our traditional physical system, which follows the laws of classical physics. But if our individual was an electron or a photon, both subatomic particles, he would be governed by the laws of quantum physics. That individual could be in all possible states at once and thus he could "observe" all possibilities in front of him.

This is one reason why quantum physics is so fascinating. It represents "the study of matter and energy at the most fundamental level. It aims to uncover the properties and behaviours of the very building blocks of nature" (Caltech, n.d.). So, quantum physics goes so deeply, in the real “building blocks” of the nature. Its properties, which will be explained in this work, are apparently contradictory, inadmissible, illogical compared to what is perceived and known by people in everyday life.

Even if "illogical", these properties have opened the way to the so-called quantum technologies, technologies that base their functionality on principles of quantum physics. Considering quantum technologies, among quantum communication, quantum cryptography, quantum sensing, we find quantum computing. This area of the quantum technologies aims to develop the quantum computer, "a computer that takes advantage of the quantum properties of qubits to perform certain types of calculation extremely quickly compared to conventional computers" (Merriam Webster, n.d.).

As it will be analysed, this is a definition, although common, rather limited. In perspective, the quantum computer is not only "faster", but it allows to realize and solve problems that today are unsolvable. Just think in the pharmaceutical field and the modelling of molecules, whose understanding of the structure is essential for the development of new drugs. A molecule of penicillin is composed of 41 atoms and for a correct modelling IBM has estimated that would need a number of bits in a traditional computer equal to 10^{86}, a

figure higher than the total number of atoms observed in the universe (Langione, Bobier, Meier, Hasenfuss, & Schulze, 2019). A quantum computer could reach at a precise modelling with about 286 qubits, the quantum equivalent of the traditional bit and consisting of a subatomic particle.
The architectural and mechanic issues of a quantum computer do not allow today to reach such a number of qubits, but once it reaches an appropriate stage of maturity, it is expected that quantum computing can solve unique problems such this one of modelling complex molecules. This potential of it is expressed by the quantum market numbers.



2020-2030 market forecast for quantum technologies[3]

If the total market value in 2020 was 340 million of dollars, a significant growth is expected for 2025, in which the market value will reach 791 million of dollars. In 2030, the market value is meant to boom, reaching about 3 billion of dollars, 1,147 billion for only quantum computing industry (iMicroNews, n.d.).

The curiosity about the topic and about new technologies led me to apply for a research position at the Observatories Digital Innovation - Quantum Technologies - of Politecnico di Milano. During this internship I had the opportunity to realize six-month research on quantum computing and the interest of this topic has involved me so deep to push myself to develop a thesis work.

[3] Source: https://www.i-micronews.com/products/quantum-technologies-2021/?cn-reloaded=1

In this paper, I tried to imagine how this technology can impact the business world. Precisely, I tried to understand how quantum computing, still premature and far from a complete realization, can impact the various business sectors and business models of these companies.

Structure

The thesis project was developed in three chapters, the first two including the results obtained from the research of the Observatory, the last one summarizing the impacts on business industries and a hypothesis on the impacts on business models. This section has been supported by a series of interviews with numerous international experts in innovation and quantum computing fields.

The first chapter describes quantum physics and its main principles, the same ones on which quantum technologies, including quantum computing, are based. Having defined the technology and the framework, the chapter ends with the technological state of the art.

The second one defines the quantum race. After an overview of global investments, there are presented the run-up to the development of high-performance quantum structures on the technology side and the development of potential use cases for demand companies.

The third chapter, after the presentation of an analysis of the disruptiveness of quantum computing, is based on the elaboration of a series of documents and the analysis of the interviews and contributions collected. The interviews allowed both to consolidate and to offer a different view of some aspects of the documents analysed. This dual direction allowed for a high-level overview of the potential impacts of quantum computing, both at the industry and business model levels.

1. The Quantum Computer

1.1. The world of Quantum Physics

«Anyone not shocked by quantum mechanics has not yet understood it»

Niels Bohr

«I think I can safely say that nobody really understands quantum mechanics»

Richard Feynman

In the first quote, Niels Bohr, Danish physicist who contributed to the development of quantum theory, affirms two things: the strange, fairy world of quantum physics and the human *difficulty* of understanding it.

In the second one, Richard Feynman, American physicist, known for his work in quantum mechanics, affirms two things: the strange, fairy world of quantum physics[4] and the human *impossibility* of understanding it.

These two different positions show how the quantum world is complex and not yet known; two of the major exponents and experts of this field didn't share the same idea about quantum theory.

Even if it could be weird, it's typical for this branch of physics not having a clear understanding of the topic.
A clear event that confirms that was in 2013, when 33 leading thinkers (mathematicians, physicists and philosophers) were submitted a questionnaire with 16 multiple-choice questions about quantum theory and its meaning (Ball, 2013). The results were surprising because answers showed how there weren't any certainties about quantum physics.

[4] He actually referred to "quantum mechanics", that is related properly to mathematical methods of quantum physics. In this work, as often used in articles and research papers, "quantum physics", "quantum theory" and "quantum mechanics" will be used as synonyms.

Said that particles (like electrons) in quantum mechanics are described as a wave function according to Schrödinger's interpretation (Helmenstine, 2019), the questionnaire was unable to determine if this interpretation is only a mathematical convenience or a physical phenomenon. Some thought «that collapse of the wavefunction during measurement is also a real process, like the bursting of a bubble; others saw it as just a mathematical device put into the theory "by hand" – a kind of trick. The Austrian poll showed that these questions about whether the act of measurement introduces some fundamental change to a quantum system still cause deep divisions among quantum thinkers, with opinions split quite evenly in several ways. Bohr, Heisenberg, and their collaborators put together an interpretation of quantum mechanics in the 1920s that is now named after their workplace: the Copenhagen interpretation. This argued that all we can know about quantum systems is what we can measure, and this is all the theory prescribes – that it is meaningless to look for any "deeper" level of reality. Einstein rejected that, but nearly two-thirds of those polled in Austria were prepared to say that Einstein was wrong. However, only 21% felt that Bohr was right, with 30% saying we'll have to wait and see» (Ball, 2013).

As a result, it is evident that even specialists are unsure about the nature of the "objects" of quantum physics. This is because quantum theory poses many unusual problems that stretch our imagination, requiring us to believe that "material" objects, such as electrons and other subatomic particles, are truly waves or particles.

Definition and history[5]

Despite the growing media hype to which it is subjected, the concept of the quantum computer is by no means recent.

In 1905, Einstein, with an experiment about photoelectric effect, suggested that light is composed of little particles, photons or quanta and in 1924, Max Born, used for the first time the term *Quantum Mechanics* (Press, 2021).

[5] Source: https://www.forbes.com/sites/gilpress/2021/05/18/27-milestones-in-the-history-of-quantum-computing/?sh=3aea2e647b23

The 1935 was a crucial year: Erwin Schrödinger devised a thought test[6] in which a cat (known as Schrödinger's cat) is announced both dead and alive. After this experiment, Schrödinger managed to explain with great simplicity a quantum physics condition and then he described that with the term "quantum entanglement".

After years of research, in 1981 quantum computers were born. Better, the concept of "quantum computer" was born. Indeed, the term was coined that year by the Nobel laureate in physics Richard Feynman after that, the previous year, Paul Benioff proposed to exploit quantum mechanics to perform calculations.

In the 80s and 90s, it was further defined and described, until Peter Shor decreed its potential, putting another milestone in the history of quantum computing: in 1994, Shor developed a quantum algorithm capable of breaking down conventional encryption, which is often based on RSA-encrypted communications, a commonly used approach for safeguarding data transmissions (Press, 2021).

The first quantum calculator was built in 1998. Using a 2-qubit NMR (Nuclear Magnetic Resonance) quantum computer, it was successfully implemented a Grover's search algorithm, a type of algorithm capable of data searching in non-structured data sets (Chuang, Gershenfeld, & Kubinec, 1998).

In the next two years IBM managed to reach a 5-qubit structure, leading worldwide research on quantum computing (IBM Research, 2000).

At the end of the first decade of 2000, the development of the first quantum hardware began: the Canadian company D-Wave was the first, in 2007, to launch a quantum chip capable of solving Sudoku puzzles.
But the major news came in 2011, when D-Wave announced the sale of its first commercial quantum computer, a 128-qubit annealer device, to global security firm Lockheed Martin. The Canadian startup was one of the pioneering companies to

[6] It will be explained in the next chapter.

successfully develop quantum hardware: indeed, in 2007 it launched a quantum processor capable of solving Sudoku quizzes (Zyga, 2011).

After hardware company D-Wave, in 2012 1QBit (1QB Information Technologies) was founded, becoming the first quantum dedicated software firm (CrunchBase, n.d.). After the nomination in 2015 as "Global Technology Pioneer" by the World Economic Forum, 1QBit is now one the most important quantum computing software companies (1QBit, n.d.).

Although it was not strictly correlated to computation, in 2014 and 2017 there were another big milestones: initially, a group of physicist at the Kavli Institute of Nanoscience in Netherlands managed to teleport data between two qubits at a distance of ten feet; then, three years after, Chinese researchers reached the same goal, but at a distance of a 1400 km satellite (Press, 2021). These experiments demonstrate the possibility to use the propriety of entanglement to safely share information along great distances, introducing the concept of "Quantum internet".

However, the transition from mathematical theory to the creation of a real quantum computer poses physical and technical challenges which, even today, are largely to be overcome. In the following years many other technological companies, including Google and IBM, launched the first prototypes of quantum computers and subsequently the first commercial offers related to development environments usable as a service were born.

1.2. The Quantum Technologies

Quantum technologies are defined as a class of technologies whose operation is based on the active design and manipulation of quantum states of matter, exploiting the principles of quantum mechanics.

Quantum technologies may appear unusual because they are fundamentally different from the reality we know and witness every day, that of classical physics. In fact, it seems strange to us to think of Superposition, a principle of quantum physics that "allows" a particle to be in several places at the same time. Just as it is strange to imagine Entanglement, another principle according to which two or more quantum particles form a unique system, where the measurement of one provides immediate information on the state of the other particle.

This strange world is the world of ultrasmall, in which all those particles, like photons, are single and indivisible. While the rules of classical physics are adequate on scales greater than the atom and speeds lower than the speed of light, outside this range the real observations do not correspond to what classical mechanics predicts: quantum physics proves to be more accurate and with vast application possibilities (Gourley, 2017).

So, understanding this world, or trying to, permits us to reach incredible and unimaginable applications. Daily we see applications of quantum mechanics: the laser, the electron microscope and nuclear magnetic resonance are all based on quantum principles. Quantum physics also help us to understand principles of chemistry, e.g. chemical behaviour of elements on the periodic table is explained by quantum mechanics (ScienceNews, 2017), and electronic wave functions used in every electronic device, specifically in transistor (Gourley, 2017).

The huge universe of quantum physics determines the world of Quantum technologies, that are classified into four types of applications: Quantum Computing, Quantum Simulation, Quantum Communication, Quantum Sensing & Metrology.

1.2.1. Quantum Computing

This area refers to all computational systems based on quantum bits (qubit), that can be represented by photons, ions, individual atoms, or quantum electronic circuits. They exploit the principles of superposition and entanglement of quantum mechanics to overcome the binary logic of traditional computation, in which a bit can take value 0 or 1 (U.S Department of Energy, n.d.). Qubit, instead, can take value 0, 1 or a combination of 0 and 1, passing from a deterministic measure to a probabilistic one. In this way, the system can process multiple inputs at the same time reducing the number of operations needed to achieve the result. If the classical computer can perform n-bit operations, a quantum computer with n-qubit can perform 2^n operations and thus can be 2^n times faster.

As a result, quantum computing enables the solution of new sorts of problems that ordinary computers cannot answer as well as the solution of traditional problems with an exponential rise in computational power. In this sense, the amount of data handled in the same period of time is enormous, accelerating database research and quantum algorithms, solving complicated equations, and recognizing clusters and patterns. Quantum computers could even «have the potential to train artificial intelligence systems, e.g., for digital assistants that help doctors to diagnose diseases and suggest the most promising therapy, or to optimise the routes of all cars in a city simultaneously to avoid traffic jams and reduce emissions» (Quantum Flagship, n.d.).

1.2.2. Quantum Simulation

«Quantum simulators can be thought of as specialised kitchen equipment that is exceptionally good at producing one type of food – perfectly cooked toast, for example» explained Prof. Lincoln D. Carr of the Department of Physics of Colorado School of Mines (Dacey, 2018). Hence, Quantum Simulation represents a type of approach to quantum computation whose goal is to solve complex quantum problems by mapping them on systems controlled in analog or digital mode. Compared to Quantum Computing, simulations are specialized and require neither universality nor fault-tolerance, thus allowing faster and more efficient scaling through specialized quantum software (Quantum Delta Nederland, 2019).

Quantum Simulators, the machine that computes operations of quantum simulation, can be specialized quantum computers, as mentioned above, or also a "imitation" of a quantum environment with the aim of modelling and understanding quantum systems.

Quantum simulators will be the «key to the design of new chemicals, from drugs to fertilisers for future medicine and agriculture, and of new materials, such as high-temperature superconductors for energy distribution without losses» (Quantum Flagship, n.d.).

1.2.3. Quantum Communication

Quantum Communication refers to communication networks that are based on quantum physical concepts. In quantum communication, the principle of entanglement plays an important role: qubits can be intertwined with each other, allowing the quantum states of particles to be correlated at great distances (Quantum Delta Nederland, 2019). Another property of qubits is that they cannot be copied with an identical superposition. Therefore, any attempt to intercept, read, and forward a qubit-based communication is traceable by comparing the received qubit states with the sent qubit states. Quantum communication is therefore potentially immune to external interference, provided that sender and receiver can identify each other reliably. This opens the way to fundamentally safe data exchange and processing. However, long-distance transmission of qubits is not easy. To address this problem, efforts are being made to develop special quantum repeaters (Ackermann, 2018).

Today it's been developing point-to-point quantum communication but, in the next years, it will achieve Quantum Internet, which will be capable of delivering data securely and at faster speeds. This technology, for example, «will help protect the increasing amounts of citizens' data transmitted digitally, for instance health records and financial transactions» (Quantum Flagship, n.d.).

Quantum Communication area comprehends Quantum Cryptography (QuantumXChange, n.d.), that provides the design of cryptographic solutions that exploit the principles of quantum physics to ensure greater security, and Post-Quantum Cryptography (QuantumXChange, n.d.), that involves the design of cryptographic solutions that can be used on classical computers but resistant to the potential attack by a quantum computer.

1.2.4. Quantum Sensing & Metrology

This field includes quantum sensors, instruments capable of observing variations in the environment, such as variations in temperature, radiation, acceleration, time (clocks) and electrical or magnetic fields. Unlike classical sensors, quantum sensors rely on quantum phenomena, such as entanglement, to detect variations. Quantum sensors are extremely sensitive and therefore allow for more precise measurements and they will drastically «increase the performance of consumer devices and services, from medical diagnostics and imaging to high-precision navigation, to future applications on the Internet of Things» (Quantum Flagship, n.d.). They are also capable of extremely high resolution, which means that tiny structures such as DNA can be measured. Quantum Metrology, instead, uses quantum sensors to define standards, e.g., time measurement or electrical measurements (Quantum Flagship, n.d.).

1.3. A new paradigm: what is a quantum computer

As affirmed before and confirmed by the scientific magazine New Scientist, «quantum computers are machines that use the properties of quantum physics to store data and perform computations. This can be extremely advantageous for certain tasks where they could vastly outperform even the best supercomputers. Classical computers, which include smartphones and laptops, encode information in binary "bits" that can either be 0s or 1s. In a quantum computer, the basic unit of memory is a quantum bit or qubit» (Lu, n.d.).

Perhaps the reason for applying quantum physics to computational computation is unclear. Are traditional computers not sufficient to guarantee the achievement of computational power comparable to quantum one?

Nowadays, complex mathematical problems are solved by HPC (High Performance Computing), that refers to the «practice of aggregating computing power in a way that delivers much higher performance than one could get out of a typical desktop computer or workstation in order to solve large problems in science, engineering, or business» (U.S. Department of the Interior, n.d.). Anyway, these supercomputers are not able to solve certain types of problems, because of the enormous amount of calculation to process.

Supercomputers are based on the aggregation of thousands of CPUs[7] (Central Processing Units), also called processors, and GPU[8] (Graphics Processing Units); in supercomputers they work together to guarantee the best performances. Physically speaking, CPUs and

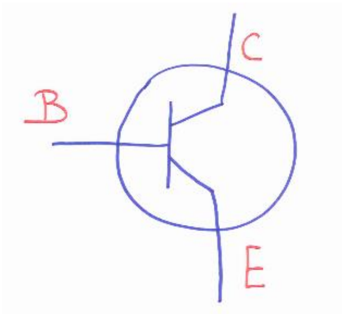
[7] "Component of a computer system that performs the basic operations, such as processing data, of the system, that exchanges data with the system's memory or peripherals, and that manages the system's other components" - https://www.merriam-webster.com/dictionary/cpu

[8] "Specialized processor originally designed to accelerate graphics rendering. [...] Originally designed to accelerate the rendering of 3D graphics; over time, they became more flexible and programmable, enhancing their capabilities. [...] "Developers also began to tap the power of GPUs to dramatically accelerate additional workloads in high performance computing (HPC), deep learning, and more." - https://www.intel.it/content/www/it/it/products/docs/processors/what-is-a-gpu.html

GPUs are formed by billions of transistors[9], semiconductors that are the base of each modern electronic device (controlling the flow of electricity) and that determine the performance of computers,

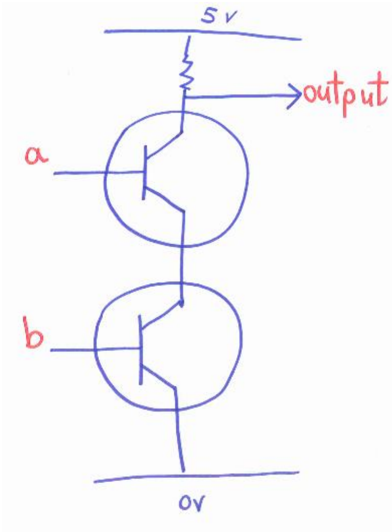
«From a systems perspective, we continue to put more and more transistors on a chip so we can have more and more complex functions, integrate them to increase performance of our systems and reduce power [...] putting more transistors on a chip is the way we can continue to bring more value, more functionality, lower cost and lower power consumption» (Khare, n.d.), as explained by Mukesh Khare, vice president IBM Research Semiconductor Group.

Essentially, more transistors equal greater processing power (and less energy consumption). This is even more clear when we consider that transistors, putting together in logic gates[10], are the physical equivalent of bits[11].

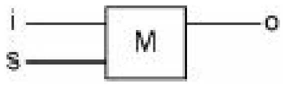


Graphic representation of a transistor[12]

[9] "solid-state electronic device that is used to control the flow of electricity in electronic equipment and usually consists of a small block of a semiconductor (such as germanium) with at least three electrodes" - https://www.merriam-webster.com/dictionary/transistor
[10] "A collection of transistors and resistors that implement Boolean logic operations in a circuit. Transistors make up logic gates. Logic gates make up circuits. Circuits make up electronic systems." - https://www.pcmag.com/encyclopedia/term/logic-gate
[11] "Unit of computer information equivalent to the result of a choice between two alternatives (such as yes or no, on or off)" - https://www.merriam-webster.com/dictionary/bit
[12] Source: https://medium.com/coderscorner/what-exactly-is-in-a-1-bit-of-digital-memory-d5395f9001a6



Graphic representation of a logic gate[13]



Graphic representation of a bit[14]

«A bit is just a place. It is nothing more than electricity being on or off. If there's no electricity in that place, then the bit is off. When electricity is present then the bit is on. So the only thing the computer can remember is whether the bit was on or off»

J. Clark Scott

1.3.1. The problem

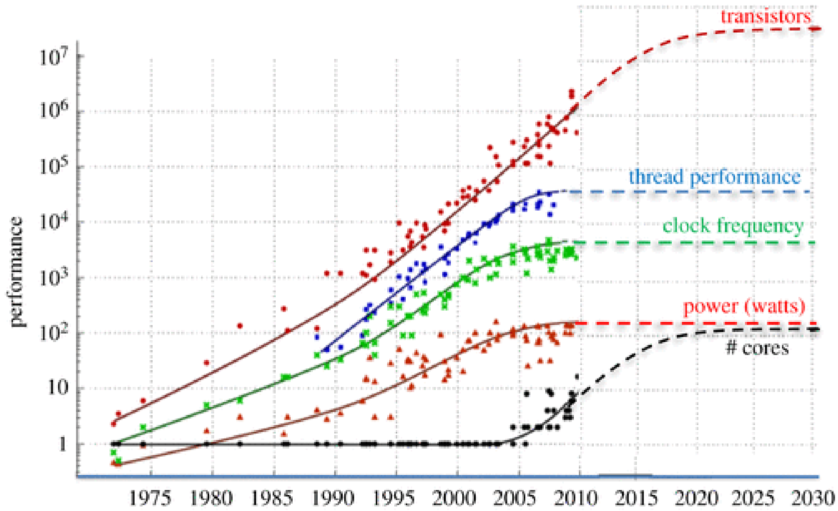
As previously said, the greater the number of transistors, the greater the computing capability. As a result, the basic reasoning is to increase the number of transistors in order to have greater processing power. However, supercomputers, like traditional ones, are facing a huge problem of transistor miniaturization that seems to break the "Moore's law" (Sterling, 2020).

Moore's law is «a term used to refer to the observation made by Gordon Moore in 1965 that the number of transistors in a dense integrated circuit (IC) doubles about every two years» (Gianfagna, 2021). Thus, the more their size is reduced, the more it is possible to

[13] Ibidem
[14] Ibidem

increase their number in the same space and therefore increase the computational power of the traditional computer.

Today, this reduction is increasingly complex, due to objective physical limits (transistors are reaching atomic scale) and in last this progression has been stopped. If the performance of digital circuits, according to Moore's law, should double every two years (considering a fixed cost and power), now this growth has been declining and it's expected to flatten by 2025 (Shalf, 2020).



The expected fall of transistors performance in the next years.[15]

It's clear that this reduction of transistors performance growth represents a challenge for the technology capability to solve difficult problems. This is the reason for the rise of quantum computing, a type of computation technology that does not follow the traditional physical laws of physics by the ones of quantum mechanics.

1.3.2. Schrodinger's cat

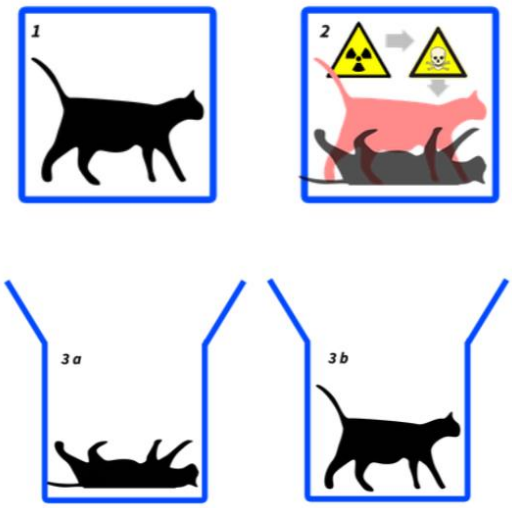
To understand quantum mechanics and the nature of qubits (the equivalent of bits for quantum computers), we can use the Schrödinger's Cat (Howgego, n.d.).

In his famous experiment in 1935, Schrödinger, the «Austrian theoretical physicist who contributed to the wave theory of matter and to other fundamentals of quantum

[15] Source: https://royalsocietypublishing.org/doi/10.1098/rsta.2019.0061

mechanics» (Britannica, n.d.), showed with extreme simplicity the potential of quantum mechanics shining a spotlight on the quantum physics interpretation.

Schrödinger's experiment is a thought experiment. He asks us to imagine a box containing a radioactive atom, a vial of poison and a cat. The radioactive atom may or may not decay with the same probability in a given time, arbitrarily defined in an hour. In this period of time, it is not known if and when the decay will occur but, once reached, this involves the breaking of the vial, the releasing of the poison and the killing the cat.



A simplified illustration of Schrodinger's experiment[16]

While Schrödinger's cat remains only a thought experiment, this represents, even if there is no uniformity of view on the part of the experts themselves, the foundation of quantum mechanics.

The experiment shows how quantum physics accepts the idea that something can exist in two different states simultaneously. Thus, the principle of quantum superposition is made explicit, according to which a quantum particle can re-enter different states at the same instant (Merriam-Webster, n.d.). Only in the moment of observation or in the

[16] Personal re-elaboration

detection of the state of another particle "linked" to the observed one here instead the entanglement principle intervenes, the actual state of the particle is revealed.

1.3.3. The Qubit

The Qubit, in quantum computers, represents the Schrödinger's Cat while it's closed into the box: unlike traditional bits which can only have two values (0 and 1), a qubit corresponds to all the values between the two extremes, at the same time, thanks to superposition. More precisely, a qubit can be defined as «a two-level quantum system where the two basis qubit states are usually written as $|0\rangle$ and $|1\rangle$. A qubit can be in state $|0\rangle$, $|1\rangle$ or (unlike a classical bit) in a linear combination of both states» (Quantum Inspire, n.d.).

Superposition property is crucial: opposing to traditional computers that, using bits, make calculus sequentially; quantum computers, with qubits, can produce parallel calculations in "multidimensional spaces" (IBM, n.d.).

So, the quantum computer completely redefines the traditional computer, revolutionizing the smallest particle of computers: qubits, which, piled together (entanglement), exponentially increase computational power.

1.3.4. The Quantum Supremacy

The aim of quantum computers is to reach a computational power now unreachable for traditional computers.

Literature has been trying to precisely define this increase of computational power, identifying some steps until speaking about "Quantum Supremacy" (Inside Quantum Technology, n.d.).
Firstly, we have the concept of "Quantum Speedup", which refers to a speedup of a quantum computer compared to a traditional one for specific problems. The speedup is classified by the capability of the quantum computer to scale as the size of the problem raises (Rønnow & al., 2014).

$$S(N) = \frac{C(N)}{Q(N)}$$

The mathematical definition of quantum speedup, where C(N) is the time used by a classical device to solve a problem of size and Q(N) is the time used on the quantum device[17]

If the speedup is significant, it's reached the "Quantum Advantage", where «a quantum computer can perform a particular computation significantly faster than even the best classical computer» (Krupansky, 2019). Meanwhile, the "Quantum Supremacy" emerges when «a quantum computer is able to compute a solution to a particular problem when no classical computer is able to do so at all or in any reasonable amount of time»[18]. To confirm that quantum supremacy has been achieved, computer scientists must be able to show that a classical computer could never have solved the problem and confirm that the speedup of a problem is "more than polynomial"[19].

Undoubtedly, these definitions are over-simplified and should be deepened, but they're adequate to understand that quantum computers have different levels of potential and maturity. Further, it's important to underline how quantum supremacy is the final goal for researchers.

Quantum supremacy «represents a pinnacle of achievement; the moment when quantum evangelists can celebrate its true arrival» (Quantum.Tech, 2021), the true arrival of the universal quantum computer. For this reason, some companies have "played" with this hype terminology, publicating studies and achievements that, actually, are extremely significant in the development of quantum hardware but not as quantum supremacy asserts.

On 29th October 2019, Google declared (Arute, Arya, & al., 2019) to have reached quantum supremacy solving «a specific task in 200 seconds that would take the world's best supercomputer 10,000 years to complete» (Paul, 2019). After that, IBM, in their

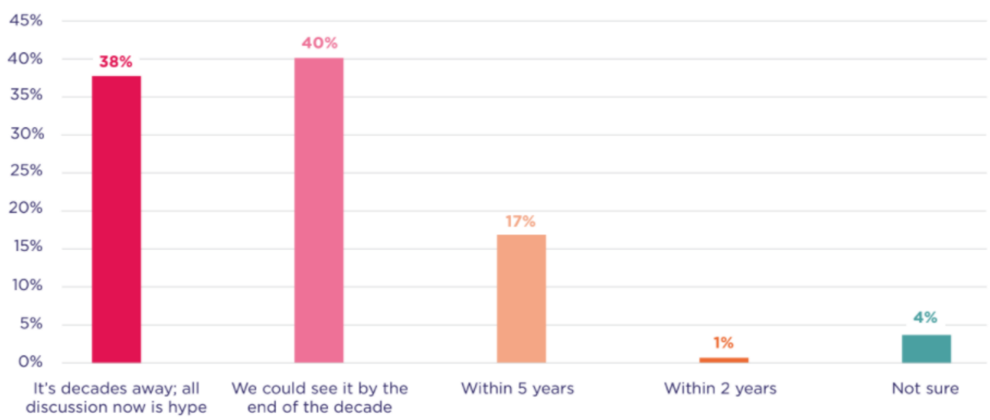
[17] Source: https://www.arxiv-vanity.com/papers/1401.2910/
[18] Source: https://jackkrupansky.medium.com/what-is-quantum-advantage-and-what-is-quantum-supremacy-3e63d7c18f5b
[19] Source: Observatory Quantum Technologies

site, published a strong statement arguing that «an ideal simulation of the same task can be performed on a classical system in 2.5 days and with far greater fidelity» (Edwin, Gunnels, & al., 2019).

In June 2021 it's the turn of a Chinese team that affirms to have estimated «that the sampling task finished by Zuchongzhi (the name of supercomputer used, ed) in about 1.2 hours will take the most powerful supercomputer at least 8 years» (Swayne, China's Superconducting Quantum Computer Sets Quantum Supremacy Milestone, 2021).

The face-off between Google and IBM has shown as there's uncertainty about the term "supremacy" and companies may overuse it to enhance the hype around the firm itself.

This uncertainty is evident in a survey produced by Quantum.Tech in partnership with Honeywell in which 100 quantum experts around the world was asked to their opinion about quantum supremacy.



Results on Quantum.Tech survey about quantum supremacy[20]

Results are clear: only fewer than 20% of survey participants believe we'll see it within 5 years; while there's equality between who believes that quantum supremacy is just hype because it's years away (38%) and who believes that could see it by the end of decade (40%).

[20] Report "Quantum.Tech, The Road to Quantum Supremacy"

While it is true there have been important speedups with devices that manage to outperform super computers in specific tasks, strong disagreement remains over the meaning of “quantum supremacy” itself, which will continue to fuel debate throughout the sector in the coming years.

1.4. Quantum computer typologies - Quantum Computer Architectures

According to IBM, there are three types of quantum computers: Quantum Annealing, NISQ (noisy intermediate-scale quantum) computing and Fault-tolerant Universal Quantum Computing. Often, the discussion of quantum architectures focuses on the Fault-tolerant Universal Quantum Computing, the one that promises to reach quantum supremacy (Gil, Mantas, Sutor, & al., 2018). It can be considered as a scaleup of the NISQ, while both Universal and NISQ are substantially different by the Annealing.

1.4.1. Universal Quantum Computer

The Universal Quantum Computer performs computational operations on quantum circuits, similar to the operations of classical computers, which can be put together to create a sequence of computations. Since it can be used for various types of problems, it is called general-purpose. However, its potentially disruptive impacts are only desirable today: current machines do not reach a volume of qubits and performance such as to be able to develop a large-scale use case (CBInsights, 2021).

Although Universal Quantum Computer are not yet ready, researchers have been able to develop a series of algorithms suitable for quantum computation. Among the most important we find Shor’s algorithm for the factorization of very large numbers and capable of breaking the cryptography, on which all computer protection systems are based today. Another relevant algorithm is that of Grover, which resolves the problem of searching in a database through unstructured data. A classic example would be searching a telephone directory for a name by having only the telephone number. If you have a classic computer, you can arrive at the name after searching half of the list on average. Grover's algorithm, which takes advantage of the superposition characteristic of qubits, can get the right answer significantly quicker (Microsoft, 2021).

1.4.2. NISQ Computer

Short-term Universal Quantum Computers have been characterised as "Noisy Intermediate-Scale Quantum Computers" by physicist John Preskill, referring to the fact that they are disturbed by what is going in the environment. "Noisy" refers to the fact that devices are disturbed by what is happening in their environment. For example, small changes in temperature, stray electric or magnetic fields can cause the quantum information in the computer to degrade. "Intermediate Scale" refers to the fact that the number of qubits will most likely be limited to a few hundred or a few thousand (Wootton, 2018). This noise causes quantum information to degrade and limits the computer size to a hundred qubits.

1.4.3. Quantum Annealer

Although IBM does not consider it a "true" quantum computer due to the limited speedup it develops (Gil, Mantas, Sutor, & al., 2018), the Quantum Annealer, developed by the Canadian company D-Wave, now a global reference point for this type of quantum computation, is a system that exploits the principle quantum for which any system tends to a minimum energy state.

Here the principle is that of Quantum Tunneling, a «phenomenon in which particles penetrate a potential energy barrier with a height greater than the total energy of the particles» (Kramer, 2020).

This approach, therefore, finds the most efficient configuration among a large combination of variables. It is therefore suitable for optimization problems, which are reformulated so that the interactions between computer qubits represent it.

The difference with universal quantum computers is substantial since it is not general-purpose and therefore can only solve specific optimization problems.

1.5. State of the art and quantum roadmapping

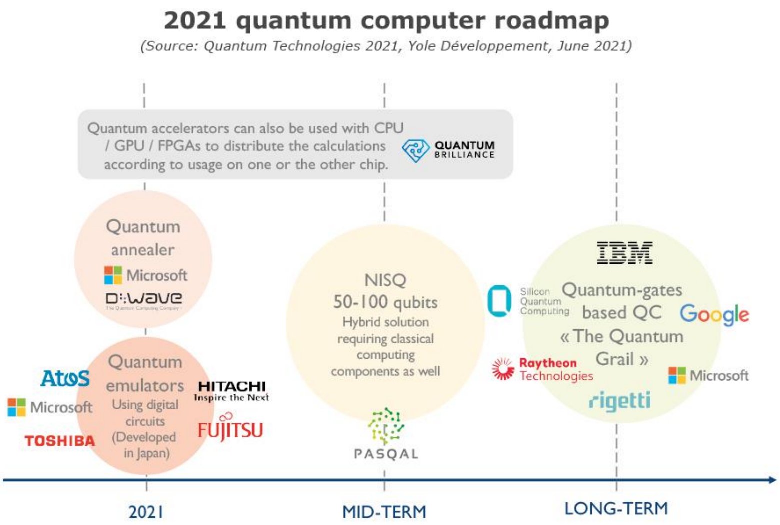
As said in previous chapter, researchers and companies are looking for a universal quantum computer. To realize a quantum computer with its properties is necessary to have a great amount of qubit and this is for the phenomenon of quantum error correction.

Quantum error correction is a process that permits to build logical qubits from physical ones for which «logical qubits are encoded in a large number of physical qubits» (Qiskit, n.d.). Logical qubits are considered the "true" qubits, those that are used in algorithmic models and that can be manipulated with absolute precision in any desired state. The logical qubits therefore represent an ideal state which, due to physical limits, are difficult to achieve. For this reason, physical qubits have imperfections and must be stacked in huge quantities to correct errors in calculations. Hence, a part of physical qubits must be used for quantum correction (Harkins, 2019).
The race for the universal quantum computer therefore relies on technological advances to add more and more physical qubits.

Now, the quantum computers marketed are those with the annealing approach and emulators.
The former is developed by D-Wave and currently surpass the 5000 physical qubits with the latest model "The Advantage" (DWave, n.d.); however, these systems are bound to the solution of specific optimization problems and therefore far from a universal approach.

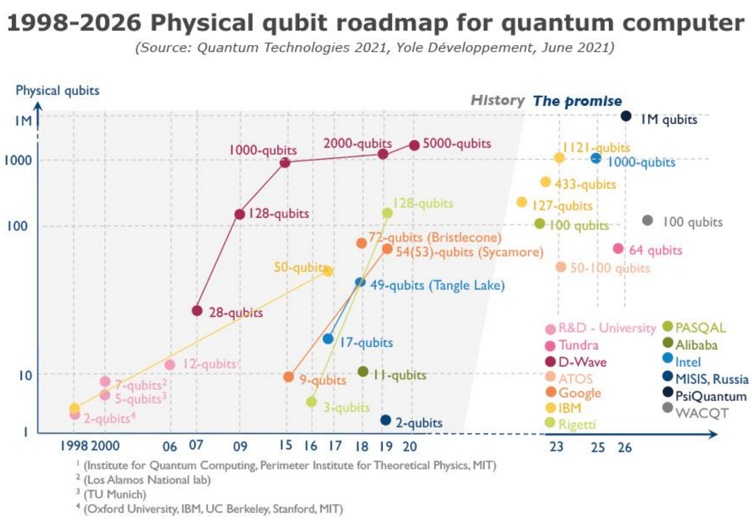
The latter are instead classic digital computers that simulate the annealing approach, NISQ and the fault-tolerant one to allow the development and study of quantum algorithms in view of the advent of these types of quantum computers. An example of an emulator is that of Atos: the "Quantum Learning Machine" can simulate up to 41 qubits (Atos, n.d.).

Next to these approaches, tech companies and startups are trying to develop both NISQ and universal fault-tolerant systems. If the NISQs are expected in the medium term with a quantity of logical qubits between 50 and 100, the "holy grail" (iMicroNews, n.d.) will be reached only in the long term when it is possible to have about 100 logical qubits, or about 100,000 physical qubits. At the moment, the most important result has been achieved by IBM, which, last November, announced "Eagle" a new processor at 127 qubits, the first to exceed 100 (Dignan, 2021).



Quantum computer roadmap[21]

As said, both tech companies and startups are racing to reach universal quantum computers and all these firms involved have drawn a roadmap for their quantum systems to predict its achievement and the intermediate steps.



Qubit roadmap for quantum computing[22]

For example, IBM, after the announcement of the Eagle processor, expects to announce Osprey in 2022, with 433 qubits, and in 2023 Condor, which promises to exceed the threshold of 1000 qubits with 1121 foreseen. The Condor processor is defined by Jay

[21] Source: https://www.i-micronews.com/products/quantum-technologies-2021/?cn-reloaded=1
[22] Source: https://www.i-micronews.com/products/quantum-technologies-2021/?cn-reloaded=1

Gambetta, IBM Fellow and Vice President, IBM Quantum, as a «milestone that marks our ability to implement error correction and scale up our devices, while simultaneously complex enough to explore potential Quantum Advantages—problems that we can solve more efficiently on a quantum computer than on the world's best supercomputers» (Gambetta, 2020).

2. The Quantum Race

2.1. The worldwide public investments

2.1.1. Methodology

The race for the development of quantum technologies is a new competitive arena for companies in the technology market. This race involves all the great global geopolitical powers that have initiated, over the last few years, a series of public research funding policies in quantum technologies, because of its large potential impacts on competitiveness and safety.

The research has mapped, in a non-exhaustive manner, the public funding allocated to quantum technologies with a past and future time horizon, from 2010 to 2030, as the sum of the policies implemented by the various countries.

2.1.2 Results[23]

Between 2010 to 2030, investments have been identified in 19.99 billion euros globally which, if focused on 2021, allow us to estimate an investment of 2.39 billion for the current year.

Most of the planned funds (15.59 billion) is expected to finance research activities over the coming decade. Although quantum technologies and quantum computing have been an active research area since the last century, the intensification of the efforts addressed for the next few years promises to support a development of the technology. Because of this, we can likely expect a growth faster than what has been recorded so far.

[23] Source: Observatory Quantum Technologies

€ 19,35 b

Global public funding for research on Quantum Technologies.
Time horizon: 2010-2030.

€ 2.31 b
- estimated for 2021

Global fundings overview for quantum technologies[24]

Canada was one of the first countries to invest in Quantum Technologies: today has a thriving ecosystem of companies and startups in this area, continuously supported through state funding to private companies.

Asia, represented for the most part by China, now holds the largest share of investments. It is followed by Europe, which has strengthened its efforts on the matter in recent years, both with the Quantum Technologies Flagship promoted centrally by the European Commission and in terms of investments by individual EU countries, such as Germany and France, which have recently allocated 2.65 and 1.8 billion euros respectively. Finally, we find the US which presents short-term loans periodically decreed and expanded in years.

As regards the Italian panorama, on 13 July 2021 the PNRR (Piano Nazionale Ripresa Resilienza - National Resilience Recovery Plan) was definitively approved. The plan, focus on the relaunch of post-pandemic Italy, includes 1.60 billion euros dedicated to the "Strengthening of research and creation of national champions of R&S on some Key Enabling Technologies", including quantum computing.

[24] Personal re-elaboration of Observatory Quantum Technologies chart

2.2. Quantum computing players

2.2.1. Methodology[25]

Research centres play a key role in the birth and growth of the quantum computing supply chain. Small and dynamic spin-offs often have been originated by these institutes and they have destined to become real startups.

From these, native players of the Quantum Computing market have developed, both at an advanced stage (D-Wave, Rigetti, IonQ, Cambridge Quantum Computing) or startups (PsiQuantum, IQM, Zapata Computing, Xanadu). The native players work alongside the players in the traditional digital market, large technology companies that have decided to extend their offer and develop quantum hardware and/or software (IBM, Google, Amazon, Microsoft).

The analysis of the players in the offer concluded with 167 players identified in the Quantum Computing market, including 25 in the traditional digital market, 43 companies native to the sector and 99 native startups.

The research methodology developed in five steps: the drafting of an initial list of players from secondary sources; the integration of this list with the contribution of the Observatory Advisory Board and the community; the analysis of the identified players; the development of a descriptive model for their analysis and, finally, the comparison with some companies in the market with the aim to validate the research.

[25] Source: Observatory Quantum Technologies

	# players	Total fundings (m)	# patents
Asia	12	€ 16	3
Australia	4	€ 40	14
Canada	21	€ 273	414
Europa	62	€ 282	108
USA	37	€ 904	348

€ 1.52 b

Total fundings (private and public) received since 2016 from 78 of the 138 native players of the Quantum Computing market

138 native QC companies analyzed

Total fundings and patents received by native quantum computing player by country[26]

The ecosystem of quantum companies can be summarized and schematized in a supply chain, defined as the Quantum Value Chain. This can be described in several design phases: the study of the technology ("enable"), its design and practical implementation ("design"), the development of quantum software suitable for the underlying architecture ("build"), the realization of integrative software between the different architectures ("aggregator") and support for the implementation of the quantum solution ("advise").

The specialization of companies in one of these phases, over the years, has helped to create a differentiated ecosystem of players in the Quantum Computing sector. By the side of research centers and major players in the digital world, traditionally oriented to the study of new technologies, we find native players in the quantum computing market (one above all, D-Wave) and startups, currently mapped in the number of 99 globally.

2.2.2. Results

In addition to the important public investments in research programs, an important contribution for the development of companies and players in the Quantum Computing market was provided by private investors. Totally, since 2016, 81 native players in the sector have been financed for an amount equal to €1.53 billion. Investors include large digital companies such as IBM and Honeywell, manufacturers of quantum hardware and software systems themselves, financial institutions such as BlackRock and Goldman Sachs, and consulting firms such as Accenture.

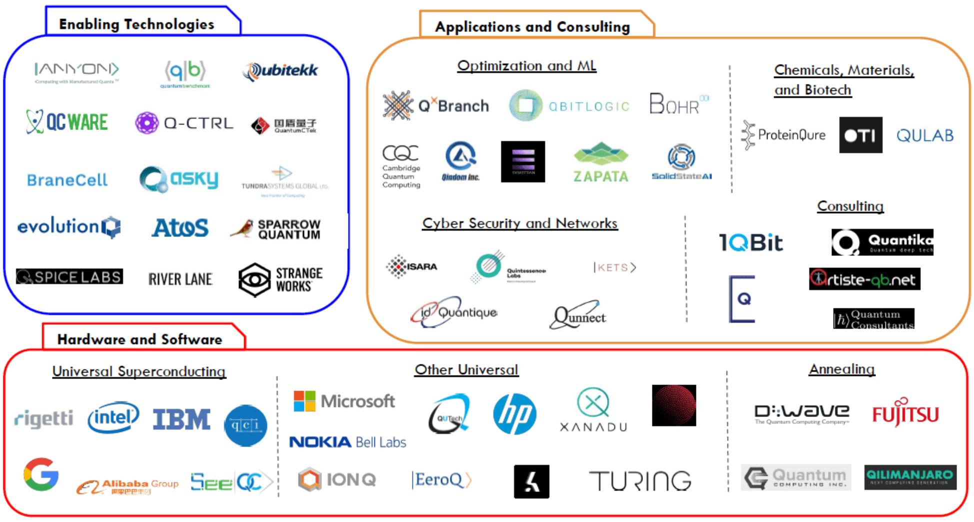
[26] Personal re-elaboration of Observatory Quantum Technologies chart

Analysing the geographical areas individually, it can be seen that Canada, Europe and the United States (considering the scarcity of information from the Asian continent, especially China) divide the records in terms of value of investments, number of total players and number of patents registered by profiled companies.

In the United States, €911 million was invested, of which €555 million in startups and €350 million in non-startup companies; while, overall, in Europe € 292 million and in Canada € 273 million. Canada also stands out for the high number of patents: 414 registered by the 21 profiled players. A more accurate analysis shows us how this number is largely due to the contribution of D-Wave, with 322 patents registered. In this sense, it can be said that Canada's early entry into the Quantum Computing market allowed local players to reach a high level of maturity.

Finally, Europe represents the area with the largest number of companies in the sector, 64 in total; of these, 48 are startups and this testifies to the great run-up that the EU is making to catch up with Canada and the USA.

2.2.3. Technology offer



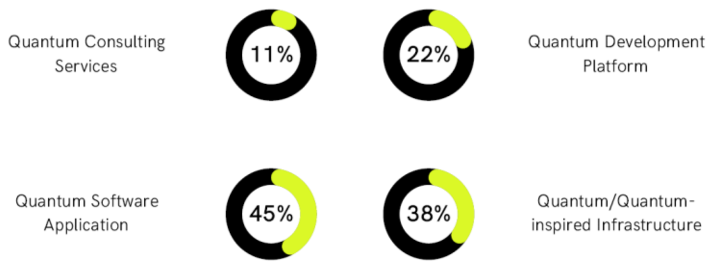
Principal Quantum Computing companies by categorization proposed by Medium[27]

[27] Source: https://medium.com/@uic126/the-bang-for-buck-with-quantum-computing-38bf2ef24b5f

Unlike three-side categorization proposed by Medium in the chart, companies mapped at the side of the technology offer have been divided in 4 categories: Quantum Consulting Services, players offering consulting services for quantum transition, in particular for post-quantum cryptography; Quantum Software Application, players offering software for developing applications based on quantum principles; Quantum Development Platform, players offering the fundamental software that makes hardware work and that provides a platform for application development; Quantum/Quantum-inspired Infrastructure, players offering quantum hardware or quantum-inspired hardware (simulators).

The mapping of the technological offer has returned an interesting look at the distribution of the services offered by the various players. Only a small part offers consulting and Quantum Development Platform services, respectively 11% and 21%; while the majority focuses on the development of quantum architectures (39%) and software applications (44%).

On the one hand, there is a wide focus on improving current quantum computers in terms of efficiency and number of qubits; on the other hand, the development of software for systems currently available but also not yet implemented. Indeed, the development of quantum algorithms proceeds even in the absence of a "ready to use" architecture; software has already been developed and hypothesized with a view to quantum-safe cryptography, as well as molecular simulation and other different fields.



Percentages of offering players by category[28]

[28] Personal re-elaboration of Observatory Quantum Technologies chart

2.2.3.1. Quantum/Quantum-inspired Infrastructure

Among the native players who develop quantum architectures we find heterogeneous realities in terms of technological development. On the one hand, companies with a already-developed and ready-for-use quantum computer: in addition to D-Wave, with quantum annealing technology, there are Rigetti, with the superconducting computer, and IonQ, with the ion-trapped computer. On the other hand, there are startups with architectures under development: PsiQuantum, which aims directly at the realization of a general-purpose quantum computer through photon technology, and IQM, which promises to make a 50 qubit superconducting quantum computing marketable by 2024.

2.2.3.2. Quantum Development Platform

The Quantum Development Platform service is very varied in its declinations, we can see companies that deal with software development kits, libraries and APIs, "quantum to classical" integrations, orchestrators and quantum operating systems. Among the most successful we find Cambridge Quantum Computing, a company specializing in the development of libraries and SDKs; Riverlane, a startup that designed Deltaflow-on-ARTIQ, an operating system that makes quantum software scalable to millions of qubits with high performances; Strangeworks, a startup that offers a platform that brings together quantum hardware and software vendors, businesses, universities, and government agencies.

2.2.3.3. Quantum Software Application

At the level of software applications, there are various players that are involved in seeking solutions in different application areas, from the financial, energy, chemical and logistical contexts. Quantum Biosystems, for example, has been experimenting the development of innovative sequencers based on quantum mechanics for DNA sequencing; Post-Quantum deals with post quantum cryptography algorithms as well as biometric solutions from a cyber-security perspective; Phasecraft is developing quantum software to study new quantum materials, helping to develop better batteries and more efficient solar cells; QuantFi deals with quantum software for the financial sector, in particular for pricing and portfolio optimization problems.

2.2.3.4. Quantum Consulting Services

A further category includes consulting services, which deal with helping companies to know and, possibly, apply the opportunities brought by the quantum computer. Among the most relevant players we can mention Quantum Thought, a consultancy startup in the field of financial services, study of materials (molecules), logistics and quantum roadmapping and Quantum Benchmark, which help the customer in choosing the best quantum hardware for the required problem.

2.3. Industries interested on Quantum Computing

As seen, the world of quantum technologies and the one of quantum computing have experienced significant growth in terms of investments and funding. This has had a great impact on the number of companies in the sector and, consequently, on the proposed use cases.

Mapping use cases gives a double point of view: the typology of problems potentially solved by this technology and companies that show interested working and making projects with quantum computing. Mapping companies, further, permit to detect industries with major impacts by this technology.

2.3.1. Methodology[29]

The methodology was based on the collecting of announcements of quantum computing initiatives from secondary sources. These sources originated at three different levels: news and announcements from the main magazines and websites for the quantum world; study of use cases public listings of major offer firms; analysis by industry of top 20 global companies for that sector.

The total number of mapped projects[30] are 80, spread over a total of 65 companies both private and state-owned from all over the world.

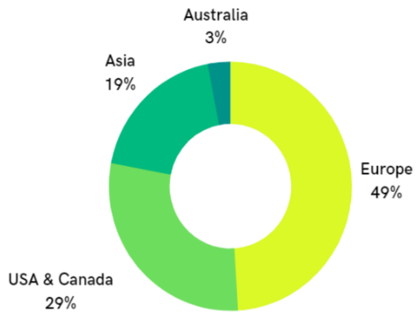
[29] Source: Observatory Quantum Technologies
[30] The listing is not to be considered exhaustive

2.3.2. Results[31]

Based on the research methodology, it can be seen how the distribution of use cases sees Europe with a percentage equal to 49% of the total cases surveyed, with AirBus (aerospace sector) and BBVA (financial sector) among the most active companies.

In the United States, which account for 25% of the cases mapped, projects in the aerospace (Air Force, Boeing, Delta Airlines, Lockheed Martin, Raytheon) and financial (Goldman Sachs, JP Morgan) fields emerge.

The remaining of the cases surveyed are divided between Asia (19%), Canada (4%) and Australia (2%); in the Asian continent various use cases emerge from Japan from companies such as Mitsubishi Chemical, Nippon Steel, Toyota.



Global distribution of mapped projects[32]

Of all the 80 cases mapped, 71 have been made since 2019 and 18 in the first half of 2021 alone; it is clear that the distribution of use cases has been concentrated in the last three years, confirming, once again, the growing interest in the quantum computing sector.
The projects surveyed can be divided into PoCs, experiments on a particular problem to be solved, which concern 70% of the total and into collaboration announcements, generic research shared by two or more partners, the remaining 30%.

These first evidences denote a market still in its beginning, in which large private companies with resources and structures dedicated to innovation have begun to experiment with technology. Their aim is to understand quantum opportunities,

[31] Source: Observatory Quantum Technologies
[32] Personal re-elaboration of Observatory Quantum Technologies chart

comparing them with traditional computing and guaranteeing a competitive advantage from the early industrialization of solutions.

2.3.3. Application areas

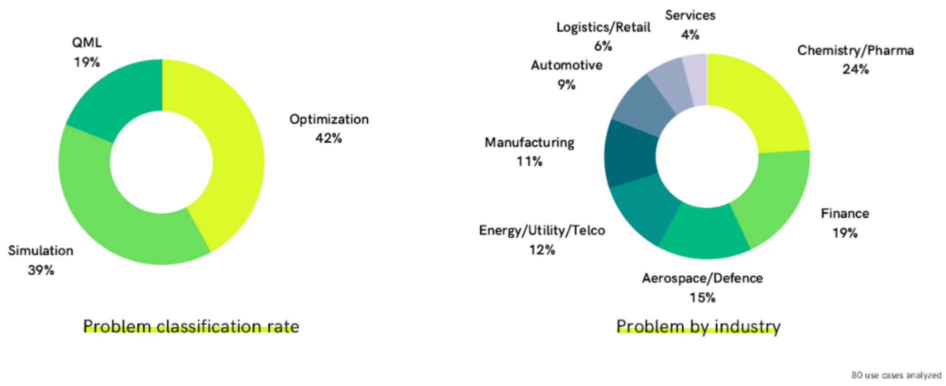
The quantum computer allows the resolution of various types of problems; among these, in the mapped cases, three macro categories have been identified: Optimization, Simulation and Quantum Machine Learning.

The optimization cases, which aim at the search for the best among a range of possible solutions, are divided into Routing Problem, for the identification of an optimal path and Resource Allocation Problem, for the identification of the optimal distribution of resources.

As for simulation use cases, which represent complex systems that cannot be reproduced with traditional computers, we can have three different sub-categories: Molecular Dynamics Simulation (simulation of molecules), Multi-scale Simulation (simulation of complex physical systems), Monte Carlo Simulation (probabilistic simulation of random variables).

Finally, for Quantum Machine Learning, an integration of quantum algorithms from a Machine Learning perspective, we can identify the problems of Pattern Recognition, for the identification of patterns within a dataset and of Classification/Clustering, for the classification of a large amount of data.

Among the surveyed cases, optimization and simulation ones are more widespread, respectively 42% and 39% of the total, while a smaller percentage (19%) concerns the problems of Pattern Recognition, Classification and Clustering. The most productive sector is the chemical-pharmaceutical sector, which holds almost a quarter of the projects, followed by Finance, Aerospace and Defence, and the Utility/Telco sector.



Partition of projects by class or sector[33]

Going deeper into the individual projects, we find that the chemical-pharmaceutical sector is more focused on simulation areas. Roche, for example, is developing software based on quantum algorithms to search for potential treatments for Alzheimer's; while Bayer, through a Pattern Recognition process, is studying the correlations between comorbidities to highlight relevant patterns in the evolution of diseases.

The financial world has also developed various projects equally distributed in the various application areas encountered, in particular the optimization of investment portfolios, the determination of financial values, risk management, credit scoring and monetary arbitrage.

For example, the Commonwealth Bank of Australia has shown, for a Resource Allocation problem, that a quantum computer can optimize a financial portfolio strategy, calculating the optimal risk and profit. Deutsche Borsa Group has instead focused on solving a Monte Carlo Simulation problem in order to calculate the risks of the shares of some companies.

The aerospace industry, on the other hand, is focused on routing optimization (of airplanes, passengers inside gates...) and simulation aimed at aircraft design. An example is U.S. AirForce, that partnered with quantum software company QC Ware for the development on quantum algorithms to unmanned aircraft survelling. Quantum machine learning algorithms could help to improve flight plans, due to the possibility to clustering and classifying objects many times faster (Inside Quantum Technologies, 2021).

[33] Personal re-elaboration of Observatory Quantum Technologies chart

The Energy/Utility world is also very promising, with experiments regarding the optimization of distribution networks and maintenance interventions, as well as the simulation of new batteries and materials for energy efficiency. ComEd, USA electric utility, is experimenting quantum computing to optimize increasingly energy complex grid.

Finally, relevant experiments are found in the manufacturing world, especially in the simulation field, as in the case of Samsung which is studying the phenomena of magnetism through quantum computing, with the aim of creating more performing batteries for consumer devices, such as cell phones and PCs.

The other sectors with quantum experiments concern the aerospace, energy/utility/telecommunications, manufacturing, automotive, logistics/retail and services industries.

		OPTIMIZATION	SIMULATION	QUANTUM MACHINE LEARNING	FREQUENCY
CHEMISTRY/PHARMA	Drug discovery - Disease pattern discovery - Material design		11	5	22%
FINANCE	Portfolio optimization - Price determination - Risk management - Credit scoring - Currency arbitrage	5	4	4	18%
AEROSPACE/DEFENCE	Aircraft design - Climb optimization - Route optimization Gate assignment - Aircraft surveilling	7	2	2	18%
ENERGY/UTILITY/TELCO	Energy efficiency - Network design - Drill path optimization - Battery design - Maintenance	2	7	1	15%
MANUFACTURING	Components - Material design - Asset sustainment - Logistics - SCM	6	1		14%
AUTOMOTIVE	Traffic optimization - Supply chain optimization - Operations optimization - Battery design	4	4	1	9%
LOGISTICS/RETAIL	Route optimization - Supply chain optimization - Network optimization - Traffic allocation	6			8%
SERVICES	Weather forecasting - Marketing content distribution	1		2	4%
		41%	39%	20%	80 use cases analyzed

Partition of projects by industry[34]

2.4. Use cases[35]

Every use case mapped includes a description of the application with a brief panel including some key information: state of the project, year, industry, and purpose, as indicated in application areas.

Some of the most important use cases are listed below, taking into account the heterogeneity of the projects purpose.

[34] Personal re-elaboration of Observatory Quantum Technologies chart

[35] Source: Observatory Quantum Technologies

Hoffmann-La Roche - Drug Discovery

State: Research & PoC Year: 2021 Industry: Pharma Purpose: Simulation - Molecular Dynamic Simulation

Roche, a Swiss multinational in pharmaceuticals and diagnostics, and Cambridge Quantum Computing (CQC) are collaborating on the design of quantum algorithms for early-stage drug discovery and development.

The multi-year agreement will implement noisy intermediate-scale quantum (NISQ) algorithms. The collaboration strives to enable the development of next-generation quantum-inspired therapies.

Roche will begin using a software platform that has built that helps simulate quantum-level chemical interactions to research possible Alzheimer treatments and, eventually, potential drugs for other diseases too.

Bayer - Disease pattern discovery

State: Research & PoC Year: 2018 Industry: Pharma Purpose: Pattern Recognition

Atos, Bayer and RWTH Aachen University announced they are working together to evaluate the use of quantum computing in researching and analyzing human disease models. They are studying the evolution of human multimorbidity diseases from large data repositories.

The project draws on anonymous real-world data from ICU patients to identify correlations between comorbidities and relevant patterns of disease evolution. This concept complements the clinical trial study approach which usually focuses on a limited number of patients and well-structured data to analyze disease criteria.

In parallel to the quantum computing approach, the Joint Research Center is running the analysis on a HPC to evaluate the accuracy and performance of the quantum experiment results.

Commonwealth Bank of Australia - Portfolio Optimization

State: Research & PoC Year: 2019 Industry: Finance Purpose: Optimization - Resource Allocation Problem

Rigetti Computing and the Commonwealth Bank of Australia conducted an experimental analysis in the financial services sector (Rigetti Computing, 2019).

The results from Rigetti and CBA demonstrated how a quantum computer can optimize a portfolio rebalancing strategy, including real factors such as the number of assets in the portfolio, total investment value and trading costs.
Also leveraging research conducted by NASA's Ames Research Center, the team was able to calculate how to achieve optimal risk and return for a small portfolio on the Australian stock exchange.

This research tests a small-scale banking problem in a simulated environment. At this scale it would not outperform traditional computers for the same use case, however, it brings the industry one step closer to understanding.

Deutsche Börse Group - Risk management

State: Research & PoC Year: 2021 Industry: Finance Purpose: Monte Carlo Simulation

Deutsche Börse has completed a pilot study into the application of quantum computing to calculate proprietary business risks, in a use case that could enter full production within the next three years.

Risk models are used to forecast the financial impact of adverse external developments (macroeconomic events, changes in competition…). Today, computation is done via traditional Monte Carlo simulation on existing off-the-shelf hardware.

A problem with 1000 inputs would require 10 years of traditional Monte Carlo Simulation and more than a few days of computation time to have no business benefit.
The study demonstrated a quadratic speedup for a small-scale version of the model. Full scale production usage would be possible with less than 200 error corrected qubits.

ExxonMobil - Maritime Path Optimization

State: Research & PoC Year: 2019 Industry: Energy Purpose: Optimization - Routing problem

ExxonMobil, one of the world's leading energy companies, faces the challenge to transport Liquified Natural Gas (LNG): it needs to be shipped 'just in time' as it is consumed, or people run out of power (IBM, n.d.).
This is an optimization problem with 2^1.000.000 of decisions combinations.

Classical computers can tackle versions of this problem by breaking it down into digestible portions and applying state-of-the-art mathematical methods. Even with this approach, it can take many hours to produce a useful solution, let alone an optimal one. Quantum computers take a new approach to addressing this sort of complexity. By partnering with IBM Quantum, the aim of ExxonMobil is to ultimately level-up the ability to tackle more complex optimizations.

Samsung - Battery design

State: Research & PoC Year: 2021 Industry: Manufacturing Purpose: Optimization - Multi-scale Simulation

Consumer technology giant Samsung, with physics researchers at Imperial College London, recently developed joint research with Honeywell Quantum Solutions to explore early-phase quantum algorithms to understand how to use quantum computing to develop better batteries.

The first experiment was carried to simulate the dynamics of an interacting spin model, mathematical models used to examine magnetism. This complex simulation required the SM H1 to run what are known as “deep circuits” and used up to 100 of the more powerful two-qubit gates.

Samsung's goal is to solve battery life problems, thus being able to produce more durable smartphones, tablets, and other devices.

Toyota - Supply chain optimization

State: Research & PoC

Year: 2020

Industry: Automotive

Purpose: Optimization – Routing Problem

Fujitsu Limited and Toyota Systems Corporation, Japanese multinational car producers, has successfully demonstrated the optimization of supply chain and logistics network operations.

They quickly calculated variables including number of transport trucks, total mileage, and parcel sorting activities, determining the most cost-effective approach for an automotive component supply chain optimization problem with over 3 million possible delivery routes.

Ultimately, the trial revealed it was possible to calculate an optimal route within 30 minutes that can potentially reduce logistics costs by approximately 2 to 5% by discovering previously unidentified distribution routes, thereby improving loading efficiency and streamlining transportation related expenses.

Save on Foods - In-store logistics optimization

State: Research & PoC

Year: 2020

Industry: Retail

Purpose: Optimization - Resource Allocation Problem

Save-On-Foods, a food retailer in western Canada, developed an experimental project with D-Wave on the optimization of the in-store logistics operations of a supermarket store.

The company's engineers approached D-Wave with a logistics problem that classical computers were incapable of solving.

After two months, the experiment resulted in a reduction in the time for some specific tasks, thanks to the use of hybrid quantum algorithm, from 25 hours to 2 minutes of calculations every week.

Even more important than the reduction in time is the ability to optimize performance across and between a significant number of business parameters in a way that is difficult using traditional methods.

3. The Impact on Business Models

3.1. Overview

The research strand of the Observatories Digital Innovation - Quantum Technologies on Quantum Computing can be outlined in some macro topics of discussion: the definition segment, in which the new approach of quantum computing was explained; the section on global investments, the part of analysis of the ecosystem of supply and demand, with the presentation of the use cases.
The use cases mapping showed the distribution of the companies on the different industries and those most active in research and experimentation of quantum computing emerged.

For this reason, it is now relevant to understand the real value of this emerging technology. Will it be disruptive, or will it play a marginal role in any market?
Which sectors are and will be most impacted, how these will be changed, how pharmaceutical and chemical companies will change, how financial companies will transform; these are all issues that this work aims to resolve.

The analysis of the literature proposed by the most important consulting firms such as McKinsey, Boston Consulting Group and some big tech companies such as IBM and Microsoft were then enriched by some contributions of international experts on the quantum theme. The aim was to push their minds a little further and ask them about the impact on the business models of these companies and what innovative business models might be. The answers, as can be expected and as will be seen in the next sections, were very heterogeneous and did not allow to give an exhaustive answer to the question of the thesis.

In any case, some of the insights are undoubtedly significant and allow us firstly to confirm the analyses of the major tech and consulting companies, but also to enrich this knowledge with unique visions.

3.2. The disruptiveness of Quantum Computing Technology

3.2.1. The uncertainty

As shown in the previous chapters, the uncertainty surrounding the quantum computing phenomenon is indeed significant. We do not know when a fault-tolerant system will actually be marketable, we do not know when the coveted quantum advantage will be achieved, we do not know the actual potential and a timeline for its advent.

And yet, the hype around quantum computing is soaring, as demonstrated by current and expected investments of 19.9 billion of euros between 2010 and 2030[36] and the size of the expected market.

Precisely because of these considerations, on the one hand we have high uncertainty, on the other high hype, it is necessary to try to identify the real value of quantum computing. In fact, according to the model proposed by Tiwana, quantum computing is characterised by a low signal-to-noise ratio, i.e., «the ratio between the identification of meaningful information on the real value of emerging technology and the hype around it» (Tiwana, 2014). Among the main factors identified by the author are two that represent sources of noise for quantum technology: technology uncertainty and timing misjudgment.
Both sources of noise can be attributed to the complexity of quantum systems.

First, decoherence greatly limits the unique properties of the quantum computer (due to the special conditions under which the hardware must remain), which is subject to «vibrations, temperature fluctuations, electromagnetic waves and other interactions with the outside environment» (Pakin & Coles, 2019). Then it must be considered the huge development costs of such systems at the limit and the current inefficiency of quantum error correction, which today allows a slow ascent towards logical qubits.

If it can be said that there is great uncertainty on the hardware side, the development of algorithms is going faster. They're numerous and of great value, such as the Groove and Shor algorithms. Therefore, there is a substantial difference in maturity between the software and hardware side, which is unable to keep up with the former.

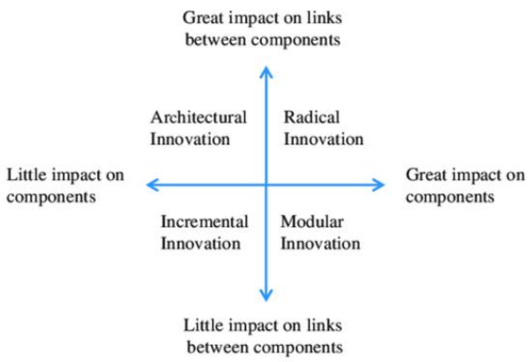
[36] Source: Observatories Quantum Technologies

This divergence is also the cause of the timing misjudgement. In fact, as Tiwana himself states, «for emerging technologies, a timing misjudgement occurs when there is an absence of critical value-generating complements by the time the technology goes on stage» (Tiwana, 2014). Timing misjudgement is therefore caused by the inability of the hardware to support what is already "ready to use", use cases and quantum algorithms.

3.2.2. The disruptive potential

Despite the noise, how is it possible to isolate and coherently assess the disruptive potential of this emerging technology?
In support of this question, there are two models: the Henderson-Clark Innovation Model and the framework proposed by Christensen.

The Henderson-Clark Innovation Model is a model that «focuses specifically on products and makes a distinction between components and architecture» (World of Work Project, n.d.), distinguishing different types of innovation.



Henderson-Clark Innovation Model[37]

The matrix (Kylliäinen, 2019) in the figure is based on two axes, the horizontal axis, representing the impacts on the components of the products, and the vertical one, representing the impacts on the connection between the components. Considering these two variables, four different types of innovation emerge: incremental, modular, architectural, and radical.

[37] Source: https://www.researchgate.net/figure/The-Architectural-Innovation-Model-AIM-Henderson-and-Clark-1990_fig1_262997824

Incremental innovation occurs where there is limited innovation to either components or architecture; modular innovation when improving a product's components without significant impact on architecture yields some but limited innovation; architectural innovation when improving a product's architecture without significant impact on components yields some but limited innovation and radical innovation when both components and architecture are innovated at the same time. In this case, radical innovation, also named disruption, takes place (World of Work Project, n.d.).

From the point of view of the quantum computer, considering this model, it is possible to identify a dual positioning for it, both modular and architectural.

Modular when one considers the processes of certain sectors, such as finance and pharmaceuticals, in which quantum computation potentially plays a key role, with the prospect of replacing classical computation in some difficult tasks. However, the substitution will not be total; indeed, the classical approach will still be predominant, and modular innovation will therefore concern some specific parts of the process.

Similarly, one can consider quantum computing as an architectural innovation when quantum applications involve the displacement of processes in order to solve more complex business problems.

In conclusion, this dual interpretation confirms the uncertainty of the value of this innovation along the value chains of the various sectors. On the one hand, quantum computing impacts specific areas, sometimes redesigning value chains; on the other hand, it does not represent a solution that completely replaces current classical systems.

To complete this analysis, it is possible to use a model proposed by Christensen. This framework derives from his book "Innovators Dilemma", where Christensen denotes certain characteristics that identify an innovative technology (Christensen C. , 1997).

A disruptive innovation (Silvestri, 2020):
• underperforms in historically most valued attributes;
• has other quality criteria;

• lower cost and margin;
• simplicity/convenience;
• low interest of established main customers;
• new first customers;
• new first vendors;
• change in the value chain.

By considering current quantum architectures and pitting them against traditional computers, it is possible to develop a high-level analysis of whether or not quantum computing is a disruptive innovation compared to classical computers.

As far as performance in historically most valued attributes is concerned, it can be stated that, apart from solving some specific and uncommon problems, specific optimisation, and simulation problems (CBInsights, 2021), quantum architecture presents considerable problems. The need to connect qubits in gates, the need to limit interferences, the need to maintain temperatures equal to absolute zero, the low degree of accuracy of the results, are all elements that lead to state that quantum computers today underperform in historically most valued attributes compared to traditional computation.

The quality criteria include, as mentioned above, the ability to solve problems that cannot be solved with traditional machines (e.g., simulation of complex molecules) and the ability to solve problems that are already hypothetically solvable, but within a reasonable time frame (e.g., complex optimisation problems). In this second case there is a measurement of the level of computational power compared to the classical one, expressed with the quantum speedup. Quantum speedup «manifests when quantum algorithms are capable of solving computation in polynomial time for those problems, like factorization of prime numbers or simulation of the time evolution of a quantum system, in which a classical algorithm scales exponentially» (Ronnow, Wang, & al., 2014). When certain types of algorithms are considered, for which speedup has already been demonstrated, it can be confirmed that these are quality criteria for quantum computers.

Cost and margin analysis is difficult to develop at a time when commercialisation is limited to cloud services with architectures with a few qubits, such as Microsoft's Azure Quantum (Microsoft, n.d.), IBM Quantum (IBM, n.d.), and Rigetti Quantum Cloud Service (Rigetti, n.d.). At the moment, the market value of Quantum Computing as a Service (QCaaS) is expected to reach $4 billion by 2025 and $26 billion by 2030 (The Quantum Insider, 2021), but it is difficult to predict the scalability of these architectures and there will probably never be on-prem structures. In conclusion, quantum computing does not seem to have lower costs and margins.

As far as simplicity and convenience are concerned, it is easy to understand, as argued above, that quantum computing is not simpler and more convenient than traditional systems, both for applicability and structural, hardware issues.

The research at the Observatory stated the presence of 167 players identified in the Quantum Computing market, including 25 in the traditional digital market, 43 native companies to the sector and 99 native startups[38].
All the big tech companies - Google, Amazon, IBM, Microsoft - are moving steadily, but at the same time there is a high number of small and medium-sized companies native to the sector and, above all, a high number of startups, which are active in terms of both hardware and software development.
From these data it can be assumed an intermediate interest by main established customers, who, until quantum computing reaches an adequate level of maturity, will maintain their focus, at market level, on traditional computing.

Considering first consumers, the debate is based on a twofold basis.
On the one hand, there are all those companies that make use of large computing machines, including Supercomputers (IBM, n.d.) and High-Performance Computers (Intel, n.d.), and that also represent the forefront of quantum computing.
On the other hand, one can consider the numerous startups in the quantum software field as new first customers of companies developing quantum architectures. In addition, it is very likely that the new possibilities opened up by quantum computing, especially in

[38] Source: Observatory Quantum Technologies

terms of materials discovery and development, will lead to the development of new companies with innovative business models ready to disrupt the market. Here, the assessment of new first consumers is at an intermediate level.

On the vendor side, we have complete heterogeneity in the supply market. As mentioned above, both large tech companies, as well as native companies and startups (not forgetting the relevant contribution of research centres, universities and academies) are heterogeneously distributed. Both established and new vendors can be found.

Considering the value chains of companies, some sectors will have new value chains in the future. For example, the possibility of creating personalised medicines in the pharma sector will substantially change the value chain. Other sectors will simply replace traditional computers for specific tasks with quantum computers. Also in this case, the level of disruption in the value chain is intermediate.

The results of this analysis intercept, once again, the uncertainty of the business potential of the quantum computer. To date, we cannot yet accurately assess the disruption of the quantum computer, not least because, as Christensen states, it's «not possible to capture market disruption before it realises» (Christensen, Raynor, & McDonald, 2015).

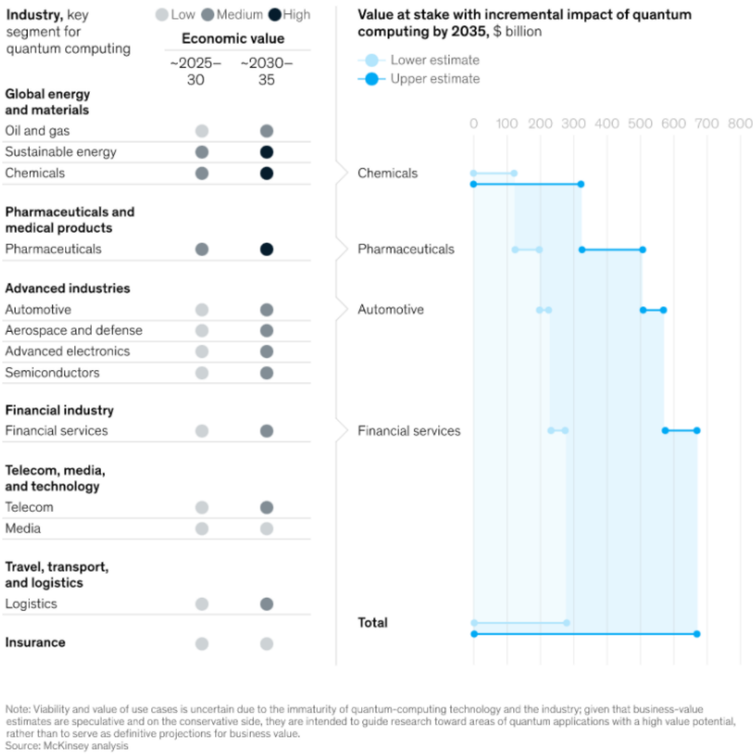
In any case, even if today the quantum computer cannot be clearly defined as a disruptive innovation due to its enormous complexity, the expectations and progress being made at the hardware and software level and the use cases developed point to noticeably exciting scenarios.

3.3. Most impacted industries

Despite the uncertainty that emerged from the analysis, which suggests a market in a hype that is not really sustained (Leprince Ringuet, 2021), great strides have been made in recent years in terms of hardware, software, and algorithmic production.
The mapping of use cases has given an idea of the application fields of quantum computing and which sectors are potentially disrupted. When the hardware architecture is able to support quantum algorithms, companies in these sectors will have to be ready and not be left behind.

Frederik Hammermeister, Partner at Roland Berger, offers another insight into which sectors will benefit most from quantum computing, depending on the data intensity of their business model. He says that «it is a question of the volume of data you have, how diverse it is and how fast it needs to be processed» (Kraft, Mittereder, & Zösch, 2021) and that he «expects manufacturing business models and supply chains to benefit the most from quantum computing, such as those in automotive, pharmaceuticals and chemicals, but it will also create new opportunities in areas like finance and transportation» (Kraft, Mittereder, & Zösch, 2021).

The McKinsey report "Quantum computing use cases are getting real" (Biondi, Heid, & al., Quantum computing use cases are getting real—what you need to know, 2021) what you need to know" identifies four sectors that could achieve major benefits in the medium term: pharmaceuticals, chemicals, automotive, and finance.



Expected economic value of several industries[39]

[39] Source: https://www.mckinsey.com/business-functions/mckinsey-digital/our-insights/quantum-computing-use-cases-are-getting-real-what-you-need-to-know

As the chart proposed by McKinsey suggests, the four industries declared most impacted, alone, could bring a shared value at stake of up to $700 billion, with a more conservative estimate of $300 billion. The pharmaceutical, chemical and sustainable energy sectors are expected to have a major impact by the end of the decade, exploding in the five-year period 2030-2035. While among those with longer-term prospects, the automotive, aerospace, financial services, telecom, and logistics sectors are the main ones.

In the following section, these sectors will be analysed due to they are considered to be most affected by quantum computing.

3.3.1. Pharmaceutical & Chemical industries

In the chemical and pharmaceutical industries, whose global market value is estimated at $1250.24 by 2021 and will reach $1700.97 billion in 2025 (Research and Markets, 2021), the impact of quantum computing is expected to be massive.

In these industries, the formulation of new substances and drugs is the core business, and the discovery of some innovative compound often determines the success of the entire company. The chemical industry spends on average 3% of its net sales on research and development, while the pharmaceutical industry spends 15% (EFPIA, 2016) and sometimes 25% (Investopedia, 2021).

The large expenditure on R&D shows how essential the development of new compounds is and, at the same time, how extremely expensive the whole process is. Scientists, even for very small molecules, find extremely difficult to accurately model them using conventional computer simulations. Even for molecules with only a few atoms, it is impossible to simulate them truthfully, and considering that proteins have thousands of atoms, most of the compounds and substances people use or consume on a daily basis cannot be simulated.

The approach is to develop molecules through synthetic chemistry processes and measure their properties. Often, the resulting molecules do not have the expected results, so the synthesis has to be repeated along with multiple tests, making the process slow and expensive (Ménard, Ostojic, Patel, & Volz, 2020).

The quantum computer has the potential to revolutionise the whole process. Thanks to its qubit structure, the quantum computer replicates the interactions between atoms. In this way, simulations can be carried out in much shorter timescales, predicting the characteristics and performance of the simulated molecules.

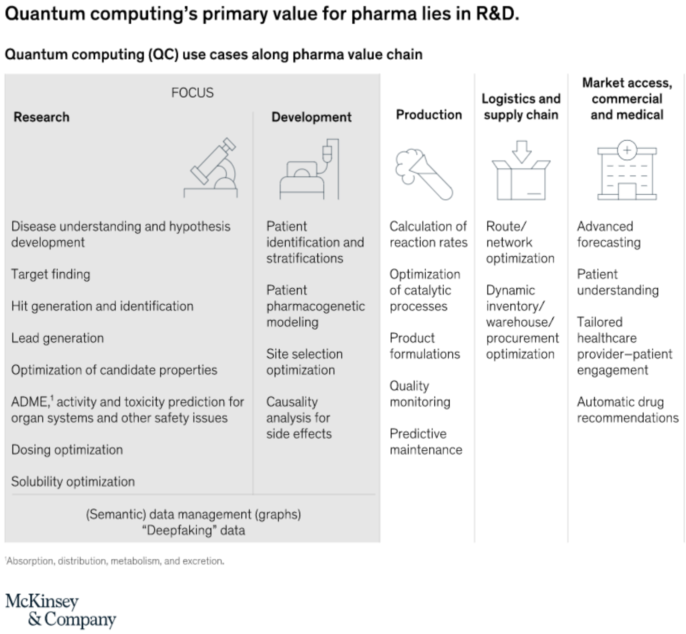
On the chemical industry side, quantum computing can help in the development of chips, fuels, plastics, and anything else that can be synthesised chemically. On the pharmaceutical side, on the other hand, the rapid synthesis of new drugs that are safe and tailored to the needs and clinical history of the patient would represent a breakthrough across the industry.

To date, NISQ, systems with limited logical qubits, have only been able to realistically simulate molecules with a couple of atoms, thus failing to reach the levels of traditional computation. With the development of computers with an increasing number of logical qubits, the impact could be extremely significant (Evers, Heid, & Ostojic, 2021).

3.3.2. Pharmaceutical industry

Major consultancy firms, such as Accenture, McKinsey, Boston Consulting Group, Deloitte, claim that the pharmaceutical sector will be among the most impacted also in the short to medium term, especially the Research & Development part.

In the value chain of a typical pharmaceutical company there are many use cases of quantum computing.



Quantum computing's primary value for pharma[40]

According to the figure proposed by McKinsey, the whole value chain will be impacted. If the areas of logistics and supply chain are transversal to other industries, it is interesting to note how quantum computing has effects on production (in product formulation and predictive maintenance for example), but also at the medical level, in terms of predictive and tailored healthcare for patients.

The main activity of the pharmaceutical industry is the development of new drugs for the treatment of various diseases and pathologies. As much as 15% of a pharmaceutical company's revenues are spent on R&D and the total R&D expenditure of the pharma sector reaches 20% of the total R&D expenditure of all sectors globally (Evers, Heid, & Ostojic, 2021).
These statistics give us an insight into the key value of an R&D company, and this is where quantum computing comes in.

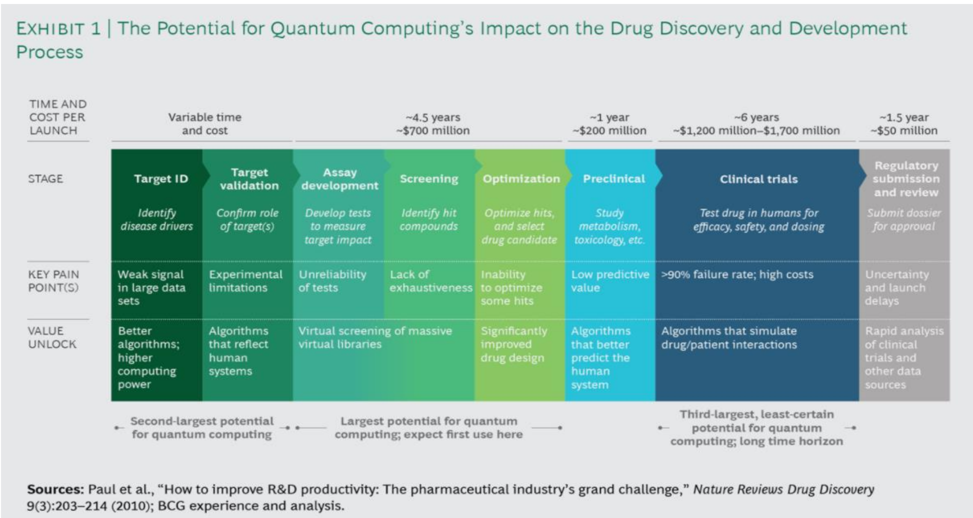
The traditional process of drug development consists of expensive, time-consuming, and risky work. On average, $2 billion is spent on the development of a new drug, the

[40] Source: https://www.mckinsey.com/industries/life-sciences/our-insights/pharmas-digital-rx-quantum-computing-in-drug-research-and-development

development time is no less than ten years and the success rate of launching the drug produced is less than 10% (Langione, Bobier, Meier, Hasenfuss, & Schulze, 2019).

For these complications, computational resources have long been used to reduce the time taken to test drugs. Indeed, various simulation processes with supercomputers and HPCs are used to model the structure of the molecules that make up the pharmaceutical compound. A problem arises when traditional computers, however powerful they may be, fail to scale up as the number of atoms in the molecules increases, so these simulations remain limited and the structures rather simple. For example, IBM «has estimated that fully and accurately modelling the base-state energy of the penicillin molecule, which is composed of 41 atoms, would require a classical computer with more transistors than there are atoms in the observable universe» (Langione, Bobier, Meier, Hasenfuss, & Schulze, 2019).

Thanks to the quantum computer and the exponentially higher calculation speed compared to traditional systems, modelling could be faster and, above all, more accurate. In comparison, if «modelling penicillin on a classical computer would take 1086 bits, it could take as few as 286 qubits on a quantum computer» (Langione, Bobier, Meier, Hasenfuss, & Schulze, 2019).



The potential impact of quantum computing on drug discovery process[41]

[41] Source: https://www.bcg.com/publications/2019/quantum-computing-transform-biopharma-research-development

The figure depicts the whole process of drug development and how quantum computing can fit into this process. As can be seen, the process is very long and risky, and the pain points are significant.

Quantum computing could fit into the different stages of the process. In terms of optimisation, researchers would be facilitated in their choice of compounds, finding the most suitable ones, excluding inactive ones, and synthesising more complex molecules. It is precisely these complex molecules that must be accurately predicted by means of these computational simulations in order to avoid ineffective drug compounds even at this stage (screening process). Another phase affected by quantum computing is that of target identification, which is extremely time-consuming in the exploration of multifactorial diseases.

A major use case is that of precision medicine, which consists of treating patients with individualised interventions and medicines. The patient's genetic and biological history affects the metabolism of the drug, which is why personalised therapies and medicines could represent a breakthrough in healthcare. Be enough to say that «31% of patients can't safely metabolise Tamoxifen, a common cancer treatment, or that there are more than 7,000 known rare diseases-affecting more than 30 million people in the United States alone-and that most of them are incurable or have very expensive treatments» (Buchholz & al., 2021).

3.3.3. Chemical industry

For the chemical industry, the reasoning is like that of the pharmaceutical industry: since we are always dealing with chemical processes, many parallels emerge between these closely related industries. In the chemical sector, quantum computing has the potential to develop and model molecules, solid systems, and polymers to a high level of precision. The approach, as for pharmaceutical companies, changes in that before synthesising a molecule in the laboratory, it can be simulated on a quantum system. The key value, once again in the short to medium term, lies in research and development (Budde & Volz, 2019).

Step	1 Design of chemicals[1]	2 Design of products[2]	3 Supply chain	4 Production	5 Marketing
Impact potential	**Early killer application**	**Early killer application**	Mature quantum computing	**Potential early application**	Mature quantum computing
Quantum tool used	• Quantum simulation • Optimization • Quantum AI[3]	• Quantum simulation • Optimization • Quantum AI[3]	• Optimization	• Quantum simulation • Optimization • Quantum AI[3]	• Optimization
Examples of future applications	• Design molecules and solid materials with required properties, reducing lab work • Use computers to define shape of proteins to make better active ingredients	• Discover more effective formulations by modeling how ingredients affect processes or how complex mixtures behave	• Use quantum computing to optimize supply chains and logistics and to reduce costs	• Improve yields and suppress by-product generation through better understanding of reactions and finding new catalysts • Use quantum algorithms to solve complex optimization problems in heat and mass transport	• Use quantum AI[3] to help handle B2B and B2C customer relations

[1]New molecules.
[2]Formulations and complex assemblies.
[3]Artificial intelligence.

Quantum computing's impact potential and tool used during value creation[42]

Applications

As the McKinsey figure shows, there are three areas of the value chain that will benefit in a reasonable time: the development of new molecules and materials, the development of new product formulations and the optimisation of production operations.

Development of new molecules and materials

The development of new molecules and materials is traditionally a slow process requiring complex calculations to predict the characteristics of the materials being developed. Currently, these predictions are approximate and only valid for molecules with a few atoms. The DFT process is used, Density Functional Theory, «a successful theory to calculate the electronic structure of atoms, molecules, and solids. Its goal is the quantitative understanding of material properties from the fundamental laws of quantum mechanics» (Kurth, Marques, & Gross, 2005).

Being a limited process, the quantum computer is proposed as an accelerator of this predictive process, opening the door to the design of materials that are not yet feasible. The current time-consuming trial-and-error process would be overturned by these precise predictive models.

[42] Source: https://www.mckinsey.com/industries/chemicals/our-insights/the-next-big-thing-quantum-computings-potential-impact-on-chemicals

The fields of development are extremely wide-ranging: new molecules for crop protection, semiconductors, magnets, luminescent molecules for OLED screens (Budde & Volz, 2019).

With a view to developing more efficient photovoltaic cells, quantum computing can be used to optimise the interaction between the sun's rays and thousands of different materials, such as silicon, polymers, organic and non-organic substances. Understanding which combination of these materials has the best interaction with light is the key to developing more efficient solar cells and LEDs (Buchholz & al., 2021).

Development of new product formulations

In addition to the creation of new molecules and materials, quantum computing can contribute to the creation of mixtures between various compounds. Here again, the typical process is trial-and-error, whereas quantum computing could optimise the production of mixtures by simulating the interaction between the various molecules of the compound with the external environment and other substances. One example is the reaction between a detergent and a certain stain: the quantum computer could predict the reaction without a necessary experiment, thus finding the best formulation to remove the stain in a matter of seconds (Budde & Volz, 2019).

Other applications include the development of OLED architectures, the production of more efficient solar cells, and the creation of absorbent materials capable of capturing CO_2 in the air. All these require hybrid efforts in terms of Artificial Intelligence, simulation and optimisation, and quantum computing would be the game-changer for these processes.

In Deloitte's “Quantum chemistry” (Buchholz & al., 2021) report, an example is cited on the process of developing ammonia-based fertilisers. This process is called Haber-Bosch, a «method of directly synthesizing ammonia from hydrogen and nitrogen, developed by the German physical chemist Fritz Haber» (Britannica, n.d.).

It is extremely important because it was the first process developed that allowed people to mass-produce plant fertilisers through the production of ammonia, enabling farmers

over the years to grow more and more food, supporting and fuelling population growth (University of Rochester, 2011).
The problem with this process is the consumption of gas, used as a fuel to reach the high temperatures the reaction requires. It is estimated that the Haber-Bosch process «consumes between 3% and 5% of the world's annual natural gas production. Producing fertilisers using the Haber-Bosch process alone accounts for 1% to 2% of the world's annual energy supply and is responsible for 2% to 3% of global CO2 emissions» (Quantum Computing Report, n.d.).
Quantum computing could simplify this nitrogen fixation process, thereby reducing gas consumption and emissions.

These are just some of the applications of quantum computing for the development of new products, the potential is enormous and could even exceed expectations: so much so that «chemistry simulations will be quantum computing's killer app» (Bourzac, 2017).

Optimising production operations
Another field of application for the chemical sector is optimising production operations. In fact, this field covers several sectors, in particular the chemical sector, which would benefit from the optimisation of reaction mechanisms and AI to uncover non-intuitive data correlations useful for the efficient generation of chemical products.

3.3.4. Financial industry

Another sector that will be greatly impacted by Quantum Computing is the financial sector. Reports from IBM, McKinsey and BCG are not strictly aligned on the timing of the impact and find it difficult to estimate an overall market value. In this sense, McKinsey goes out of its way to state that the value at stake of the financial sector by 2035 will be between 50 and 100 billion dollars (Biondi, Heid, & Henke, Quantum computing use cases are getting real, 2021).

In any case, the high number of use cases, highlighted by both the Observatory's research[43] and McKinsey's report, suggests that attention is high and the impacts potentially high (Ménard, Ostojic, Patel, & Volz, 2020). IBM also points out that this race

[43] Source: Observatory Quantum Technologies

to develop use cases is also determined by the possibility of being a first mover on the market (Yndurain, Woerner, & Egger, 2019). An example that IBM itself gives is the possibility of possessing algorithms that detect potential arbitrage situations that competitors do not intercept. But the interest in the financial sector for Quantum Computing does not refer exclusively to this situation.

Quantum computing will, on the one hand, make it possible to solve problems that are simply intractable today on even very powerful classical computers. On the other, it will improve the quality of the outputs that financial institutions are already able to compute on HPC architectures, while hopefully reducing execution times and the overall energy impact of these computations. Most of the use cases that characterise the financial industry have a high computational complexity and therefore lend themselves to quantum computing.

Among the possible groups of use cases, besides optimisation problems such as arbitrage or financial portfolios, scenario simulations represent a great possibility since they leverage the intrinsic ability of quantum hardware to generate truly random numbers. Some promising quantum versions of machine learning algorithms could also make fraud detection systems or systems for forecasting macroeconomic and financial variables more accurate and almost real-time. And let's not forget the possibility of optimising clients' decision-making with a view to KYC, a «standard in the investment industry that ensures investment advisors know detailed information about their clients' risk tolerance, investment knowledge, and financial position» (Chen, 2021), protecting both clients and financial institutions, since it is a process issued to subjective assessments and human error.

Financial use cases can be grouped into three main categories: targeting and forecasting, trading optimisation and risk profiling.

Targeting and forecasting

Today, customers of banks and financial institutions demand personalized financial products and services. Financial institutions are struggling to create behavioural data

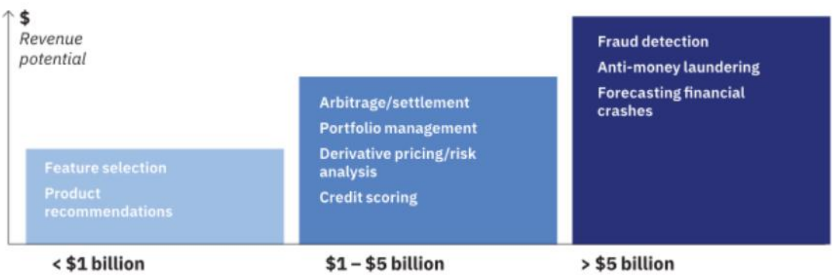
models to trace the products customers want. In this sense, quantum computing could help with predictive analytics and companies could expand their customer base.
A similar problem is that of fraud detection. The process of customer onboarding (credit score evaluation) is lengthy and cumbersome; indeed, it can take up to 12 weeks to produce an accurate result. Speeding up the process, fraud detection systems remain highly inaccurate. In fact, it is estimated that financial institutions lose between $10 billion and $40 billion a year in revenue per year (Yndurain, Woerner, & Egger, 2019). Again, quantum computing would allow for more accurate predictive models.

Trading optimisation

Increasing complexity is emerging for financial market trading activity. To include an increasing number of variables and limits and accurately simulate different scenarios, money managers face significant computational constraints. In this sense, quantum computing could optimize portfolio diversification by quickly balancing investments against the instantaneous change of the variables.

Risk profiling

For financial institutions, a relevant problem is the increasing difficulty in managing risk. For this reason, directives, regulations, and standards (Basel III and various revisions) are overlapping to increase risk management stress scenario simulations. For these increasing risk-profiling demands, quantum computing can accelerate and improve the accuracy of risk scenarios (Yndurain, Woerner, & Egger, 2019).



Revenue potential by financial services activities potentially benefiting from quantum computing[44]

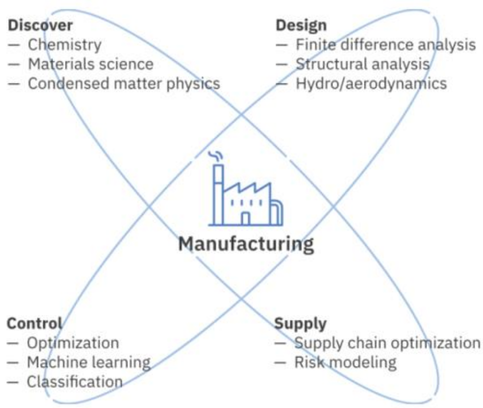
[44] Source: https://www.ibm.com/thought-leadership/institute-business-value/report/exploring-quantum-financial

3.3.5. Other industries

Other relevant sectors for quantum computing are automotive, logistics and manufacturing.

For automotive, in the short term, the most interesting applications are “vehicle design optimization”, for optimizing engineering analysis to reduce material weight, and "minimizing vehicle inventory”, for inventory optimization that could reduce the millions of finished vehicles not sold in showrooms. In the long term, batteries are a relevant issue for the industry, and in this, quantum computing could be of great value increasing energy density of batteries. Autonomous driving will also benefit from quantum computing due to its ability to handle huge amounts of data and millisecond analysis capabilities (Martin, 2021).

In logistics, routing optimization is the priority. The variables are so numerous and complex that efficient solutions cannot be given. Quantum computing potentially has the capabilities to handle complex optimization problems in minutes versus thousands of years on a supercomputer.
In this area, DHL has already developed POCs in order to optimize parcels and global delivery routes, thereby improving speed and quality of service (CB Insights, 2021).
Manufacturing sector includes various applications that bring together cross-industry optimisation, simulation, and quantum machine learning problems.



Main IBM’s manufacturing applications for quantum computing[45]

[45] Source: https://www.ibm.com/thought-leadership/institute-business-value/report/quantum-manufacturing

As presented in the figure proposed by IBM, the manufacturing applications fall into four categories: discover, design, control, supply.

The discover category focuses on problems relating to the simulation of molecules, with the aim of developing materials with higher strength-to-weight ratios, batteries with higher energy density, and the efficiency of synthetic processes. One area of study that is gaining ground is the mimicry of natural materials, which aims to artificially replicate materials produced in nature (Modjarrad & Ebnesajjad, 2014). One example is spider silk, which is stronger than steel on a per-weight basis and could be produced at room temperature instead of in a furnace (The Conversation, 2013). Quantum computers could help simulate the molecular structure of spider silk and allow its artificial replication.

In terms of design, many manufacturing industries such as aerospace develop 3D models of components and sub-components to study their interactions, other than chemical and physical behaviour. Through quantum simulation, the interactions between components could be much more accurate, allowing more variables to be analysed.

Today's control processes are limited by the ineffectiveness of traditional computers to correctly evaluate all variables: quantum machine learning and quantum optimisation could find new correlations and patterns and thus optimise, for example, production flows and robotics scheduling for complex products.
In terms of supply, quantum computing could help real-time market demands models by increasing the speed of decision-making and decreasing the risks of out-of-stock or discontinued products (Woerner & Kesterson-Townes, 2019).

3.4. Voice to the experts

The use cases and the impact on the value chains of various sectors show that quantum computing has a high potential for some industries, such as the chemical-pharmaceutical one, but a lower potential, at least in the short to medium term, for sectors such as logistics and manufacturing.

The unknowns of this technology, since it is still at the research stage and to physical problems that are difficult to overcome, do not allow us to have a clear vision of the future. It is not clear what type of architecture will dominate, whether there will be one, the costs, interoperability with classical systems, the ability to overcome the physical limits imposed by quantum physics, and the timing of development.
These are some of the doubts that emerge from the sources analysed and which are shared by the same experts in quantum computing.

While the work carried out so far has focused on giving a general overview of quantum computing, identifying its state of the art, and understanding how the various sectors can be impacted by this technology, the final step has been to consolidate what has been described in this paper and, as far as possible, to go one step further. For this last section of the thesis, the aim has been to gather some opinions from experts on quantum computing and innovation visionaries.

The idea for this last part was based on asking this selection of experts about the impacts on the business models of various companies and what might be innovative business models. As can be imagined, it has been difficult to come up with clear and well-defined visions: the stage of this technology is still too early to think of plausible business model scenarios.

Discussions with experts often remained at a higher level, like general impacts on various sectors and potential use cases. In any case, many insights have emerged, which, aggregated and analysed, can help to provide a key to understand what the business value of quantum computing will be, particularly at the business model level.

3.4.1. Interview methodology

The research approach was based on interviews and textual contributions at various levels and with an increasing level of specificity.
Three parameters were used to structure the research: firstly, the type of company the interviewee came from, secondly, the type of questions and discussions addressed, and thirdly, the type of contribution. In the first phase, the interviews focused mainly on experts from large consulting firms (Accenture, Deloitte, Strategy&) with general, high-

level questions. In the middle phase, the focus was on supply-side companies (IBM, NTT Data, Atos), while in the last phase, the focus was on demand-side companies (BASF, Roche, Intesa San Paolo). Furthermore, it must be stressed that not all contributions came from interviews, but also from exchanges of messages via email or via LinkedIn platform. Doing so, the research was extended to more profiles.

The insights were of various levels. Firstly, the consultancy profiles provided a high-level cross-sectoral overview and allowed the research to be directed towards those sectors, aspects and issues that have been most relevant to investigate. Secondly, seeing both sides, the supply and demand side, brought a more stringent and singular view.

The companies targeted represent realities that have started to approach the world of quantum computing. In this case, there were two main selection criteria: companies mapped in the research at the Observatory or companies that are among the world's leading companies in terms of size in their sector. If in the first case there is public knowledge of their involvement in projects and/or collaborations on quantum computing, in the second case it was assumed that a company of a certain size is at least aware of the topic.
After identifying the target companies, the research moved on to the experts. Using the LinkedIn platform, applying filters by sector or by specific company, medium-high level profiles were sought in the fields of "Innovation" or "Quantum technology". Some of the respondents, on the other hand, came via direct contact.

The list of contributing experts is below, followed by the job position, company and type of contribution, interview or text.

Consultancy

Alan Martin - Founder & Principal at Psi-Ontic - Interview
Arne Hollman - Senior Associate & Quantum Technology Expert at Strategy& - Interview
Davide Venturelli - Associate Director, Quantum Computing at USRA, NASA Ames Research Center - Text
Emmanuel Viale - Managing Director at Accenture - Interview
Giuseppe Giordano - R&D Senior Manager at Accenture Labs - Interview

Roberto Siagri - President at Carnia Industrial Park, Co-Founder at Eurotech - Interview
Scott Bulchoz - CTO at Deloitte Government Practice, US Consulting Quantum Leader, Emerging Trends Research Director - Text

Offering

Alberto Acuto - Technology Strategist, Office of the CTO at NTT DATA - Interview
Federico Mattei - Client Technical Leader andQuantum Ambassador at IBM - Interview
Heather Higgings - Partner, Quantum Industry & Technical Services at IBM - Interview
Ingmar D'Amato - Senior Expert: Advanced Computing (HPC, AI & Quantum) at Atos - Interview
Najla Said - Solution Architect at Serco - Interview
Robert Sutor - Tech Leader | Quantum Computing | AI | Python | Author | Keynote Speaker - Interview
Tommaso Demarie - Co-Founder & CEO at Entropica Labs - Interview

Demand

Brad Kim - Head of Quantum Computing Application Team at LG Electronics - Interview
Bryn Roberts - SVP & Global Head of Data & Analytics at Roche – Text
Cedric Membrez - Emerging Technology Researcher, IT R&D at UBS - Text
Daniel Volz - Quantum Computing at BASF - Interview
Davide Corbelletto - Quantum Technology Specialist at Intesa Sanpaolo - Interview
Durga Prasadk - Machine Learning Architect at Bank of America – Text
Marco Rancic - Head of Quantum Computing at TotalEnergies - Text
Jacek Lukawy - Innovation Program Director at Novartis - Text
Lorenzo Ferrone - Data Scientist at FSTechnology at Ferrovie dello Stato Italiane – Text

The style and questions of the interviews changed as the number of interviewees grew. These valuable comparisons, on the one hand brought out new ideas to be explored, and on the other allowed to focus and standardise the research on some specific questions, especially for the contributions of demand side companies.

What changes for *related sector* industry with the coming of QC. What the potential impact of QC on business models is. Which BM building blocks could be impacted. What innovative BMs could be created. How *company name* is getting ready for this coming "revolution".

Once collected experts' comments, the work continued by summarising their interventions and schematising the most relevant insights in an Excel table. In this way, it was easier to analyse the most relevant patterns and to find information that could be included in a more specific reasoning on business models.

The insights are mainly divided into high-level information on quantum computing, on the market, on a specific sector or company and finally on business models. These will be presented without a precise reference to the interviewee but with an overall approach.

3.4.2. Relevant considerations and patterns emerged from interviews and contributes

In this section we will discuss a series of macro-topics that echo what has already been explained but enriched with a number of relevant insights from the interviews. These insights often confirm what has been explained in the previous chapters, but on other occasions they are new.

Technology value

At the technological level, it is clear that a quantum computer is a *long way off*, or at least not close, *from having a significant impact on companies*. The reason is structural: it's needed millions of qubits to achieve the quantum advantage. As mentioned in the first chapter, it is necessary to achieve many qubits in order to devote a certain number of qubits to error correction and to have "logical qubits" (Harkins, 2019).

In the short term, even at the architecture level the debate is open, with the annealing system finding a place especially in the financial sector. It turns out that *at the moment, annealing is more powerful, but this does not mean that the cost-benefit is positive*. By solving only a few, specific, problems and having to adapt them to an analogic approach

(Pearson, Mishra, Hen, & Lidar, 2019), quantum annealers are *generally considered to be less versatile*. Despite this apparent paradox, quantum annealers are currently considered to be much more rooted and performant in the financial sector, especially since they have been on the market for longer, thanks to DWave.

One concrete thought that emerged was to treat quantum computing as a technology that is still too embryonic to discuss future benefits. There is *not much point in talking about what the benefit will be, it is necessary to "tweak"*. The reflection was accompanied by parallels with the story of the *Wright brothers*, the two US engineers and inventors considered to be the first to have successfully flown a powered machine in a sustained and essentially controlled manner. Compared to the attempts of earlier years where the focus was immediately on the motorisation of the aircraft, the Wright brothers had the intuition to concentrate on the problems of surface aerodynamics and flight control, and only then to concentrate on the installation of an engine in the aircraft (History, 2009). This leads to reflect on the fact that it is necessary to experiment and develop a suitable quantum architecture before it can be possible to focus on business impacts.

Market effects

Several insights, some unexpected, have emerged into the quantum computing market ecosystem.

The management of the largest companies are getting closer and closer to this technology: *CEOs are asking to be ready*. There is therefore a shift *from awareness to readiness*. Even if there is no real impact at the moment, companies want to be there as soon as there are major developments in quantum computing. In this sense, two main strategies are being identified: *first-mover* and *fast-follower*. The first leverages on large investments to increase the necessary hard skills and to start experimenting with PoC, especially algorithms. The second coincides precisely with the awareness mentioned earlier, in clinging to the latest technological and market developments in order to be ready as quickly as possible.

From the point of view of the players on the supply side, *the shared idea emerged that the hardware players are already well-defined*. As emerged from the Observatory research[46],

[46] Source: Observatory Quantum Technologies

only 26 of the 167 mapped supply players develop quantum hardware systems. Looking at the companies present, we see that the vast majority are well-structured players such as IBM, Google, AWS, Microsoft, DWave. Thus, two needs emerge for companies on demand side: to rely on an as-a-service system, instead of developing their own hardware, and to effectively navigate among all the types of hardware on the market. In this sense, orchestrators are critical. They represent platforms that «provides automated configuration, coordination and management of complex computing networks, systems and services» (sdxcentral, n.d.). In the case of quantum computing, we deal of Quantum Orchestrators, as is Strangeworks, a hardware-agnostic platform that makes it possible to experiment and develop quantum algorithms by choosing the most suitable hardware. So, companies are not and will not be interested in the *back-end*, but will rely on platforms like Strangeworks to choose hardware on a case-by-case basis (Strangeworks, n.d.).

At the value chain level, there will be *fragmentation* between the various sectors impacted by quantum computing. If, as mentioned above on the hardware side, a concentration towards the tech giants is expected, on the software side there are numerous startups (58 of 99 startups according to the Observatory's research[47]) developing quantum software and algorithms. The algorithm, in fact, *once written is cheap* and can also be developed by startups. They can develop code for companies, even large ones, which then risk losing their competitive advantage. This is precisely one reason why a quantum race has been created to keep up with the hardware and algorithms created.
In support of this, from the perspective of both the chemical and pharmaceutical industries, it has emerged that startups or even client companies could *take over key activities*. On the chemical side, the example is that of *automotive companies that could develop the essential simulations themselves* to optimise and improve batteries, engines, emissions, fuel, without the need for the chemical supplier. On the pharma side, startups could also develop algorithms for the simulation of medicines and treatments, in which sense pharmaceutical companies risk losing their competitive advantage and changing their core business towards *large-scale production* only.

[47] Source: Observatory Quantum Technologies

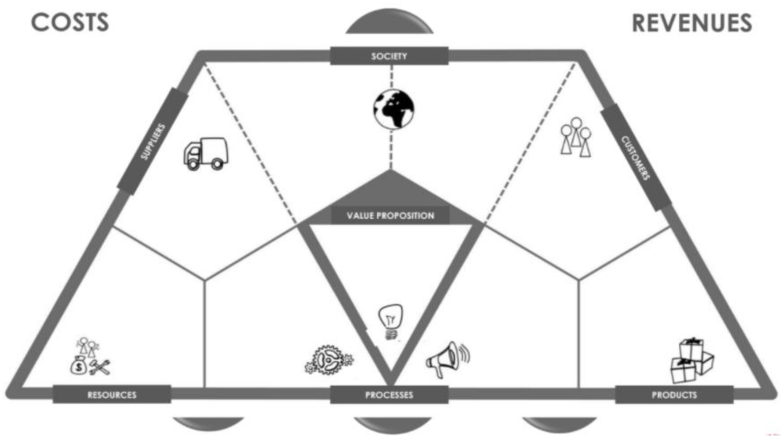
Finally, quantum computing could have geopolitical implications: there is the possibility of moving “*from the age of extraction to the age of creation*”. With the possibility of creating materials from scratch, it would no longer be necessary to depend on other countries for the supply of materials, minerals, rare earths, and other resources; just think of the US dependence on China, especially for the defence industry. This scenario is certainly unsettling and will have to be considered very carefully.

3.4.3. Business models impact analysis

After assessing the macro impacts at technological, market and sectoral level, it is interesting to analyse from the insights gathered the potential impacts that companies may have on their business models.

The model on which this analysis was developed is the Business Model Canvas "revisited" by Prof. Carlo Bagnoli in the book "I modelli di business vincenti per le imprese italiane nella quarta rivoluzione industriale" (Bagnoli & al., 2018). This model, originally developed by Dr. Alexander Osterwalder, is defined as «a business tool used to visualise all the building blocks when you want to start a business, including customers, route to market, value proposition and finance» (University of Oxford, n.d.).

In Prof. Bagnoli's review, the business model canvas presents 8 building blocks plus 2 areas corresponding to costs and revenues.



Redesigned business model canvas[48]

[48] Source: Bagnoli, C., *I modelli di business vincenti per le imprese italiane nella quarta rivoluzione industriale*, 2018

In summary, the 8 building blocks are described as follows (Bagnoli & al., 2018):

I. *suppliers*: parties or organisations with which the company establishes relations for the procurement of resources that are necessary to feed the company processes and that it does not have available;
II. *resources*: physical economic assets, financial resources and intellectual resources needed to feed the processes;
III. *internal processes*: system of activities that the enterprise develops to transform inputs (resources) into outputs (products);
IV. *products*: visible offer with which the enterprise presents itself on the market to satisfy the explicit (response), latent or non-existent (proposal) needs of customers;
V. *communication channels*: channels with the aim of increasing product awareness and evaluation capacity;
VI. *customers*: recipients of the products, who certify or otherwise the validity of the company's value proposition;
VII. *society*: the set of company stakeholders (employees, citizens, researchers, etc.) whose opinions, decisions and behaviour may favour or hinder the company).

In these blocks are inserted the costs, which represent the outputs with respect to the structure of the business model, and the revenues, the way in which the company makes income.

The methodology was based on incorporating relevant insights into a business model analysis and then grouping them according to individual building blocks. For this analysis, it was supposed to consider the impacts to companies only from demand-side, focusing in the most affected sectors. Further, it has been assumed a hardware maturity to have a quantum advantage.

Insights

Autonomous creation of materials

Thanks to developments in the field of simulation, some companies (such as the example cited above for the automotive sector) will be able to develop molecules, substances, and raw materials for their own production processes in-house, without having to make use of chemical companies.

Increased need for suppliers

The barrier to entry for the supply of algorithms and software is limited and many startups are already in the market today. This is due to a limited barrier to entry where the only real need is for expertise. Access to hardware in the cloud is not particularly expensive and experimentation of algorithms can still be performed in classical hardware, simulating quantum environments. As a result, the entire value chain, including the supply chain, will be fragmented. In fact, companies may have to rely on a large ecosystem of suppliers to meet all their needs in terms of applications and algorithms.

QaaS

The architecture of quantum computers has an enormous cost. This has meant that supply-side players are more or less defined and that demand-side companies cannot develop an on-premises quantum system.

Numerous cloud services, Quantum-as-a-Service (QaaS), are already on the market and allow remote access to the quantum computer. It is estimated that Quantum Computing as a Service market will reach $26 billion by the end of 2030 (The Quantum Insider, 2021). This is expected to be the main usage model in the future as well, as the costs of building on-premises hardware will be inconvenient compared to cloud.

Partnership ecosystem development

Quantum computing, due to all the barriers and difficulties currently present, requires a continuous and extensive exchange of information between various players to allow the growth of the entire ecosystem. Today, working in quantum computing without collaborating with the outside world is a self-defeat. The *development of an open-source ecosystem* also requires an effort in social terms, as probably no technological innovation has required such a strong paradigm shift.

Finding expertise in the market

The high complexity of quantum technologies is driving companies to search for high-profile experts, currently with great difficulty; new figures such as quantum engineers are still extremely rare. Companies must now reach out to as much human capital as possible and consolidate it soon.

Internal development of new skills

One of the greatest difficulties today is to possess the capabilities needed to work with quantum computing. Capabilities in the market are very limited in number, so another path for companies must be to build up new internal quantum skills. Not only researchers, but also all other business units cannot be excluded from this up-skilling, even if with high-level knowledge.

Greater efficiency in all internal and external processes

While quantum simulation is mostly sector-specific, quantum optimisation covers all sectors. In fact, any company needs to optimise its internal and external processes, especially the former. Internal processes could have great benefits by accelerating product innovation, increasing productivity, and reducing waste. In this sense there is also *greater sustainability efficiency* that can help the company to use fewer raw resources, have a more efficient supply and logistics system and manage the production chain more easily.

The most impacted external process coincides with the optimisation of the distribution of the product, in particular the physical one.

Patents

If the risk of fragmentation of the value chain is high, companies, especially large ones, will have to protect the output of their research through patents. For chemical-pharmaceutical companies, newly developed materials or algorithms need to be protected to maintain their competitive advantage.

New processes

Companies, especially chemical and pharmaceutical ones, will have to restructure some internal processes, such as R&D, radically transformed in terms of research methodologies, computational infrastructure, and human capital.

More attention to risk management

Quantum computing poses a major threat to any company. Quantum computing has the potential to disrupt modern cryptography due to its immense computational power. The subject of quantum cryptography is extremely relevant, and algorithms that can protect against quantum computing have been studied for years. Financial services are already paying attention to this issue and are investing resources in research into codes for post-quantum cryptographic protection and risk management.

New products

Customers could have new products thanks to quantum simulation processes, and this impact would affect various industries. More efficient photovoltaic cells, new personalised medicines, new batteries, new sustainable fertilisers are just a few examples.

New services

Financial services could become software and algorithm producers and offer new services such as financial quantum algorithms. In this case, early developers could become market leaders. Also new realities like startups could carve out an important role with the development of optimisation algorithms and provide an *optimisation as a service*.

New customer segments

In the chemical and pharmaceutical industry, the possibility of creating new substances and materials can lead to collaboration with new customers. An example would be a collaboration between a chemical company and a CPG one to improve product development. This integration would favour the production of better products, such as shampoos and cosmetic products.

Impacted building blocks

Suppliers

This building block will be impacted across all sectors in terms of demand for the cloud service. The QaaS model can be used in the platforms of the offering company, thus using its own hardware (IBM, Rigetti, DWave), or through orchestrators (Strangeworks) that allow easy switching between one architecture and another. Collaboration with these

suppliers, as well as research centres, universities, consultancies, competitors, and startups, contributes to the development of an extended partnership ecosystem, where companies collaborate with both hardware and quantum application providers to develop POCs and POVs.
The fragmentation of the entire value chain includes the supply chain and leads to fragmentation of suppliers. In line with the growth of the partnership ecosystem, a broad diversification of suppliers of quantum algorithms and applications can be expected.

The chemical-pharmaceutical industry may be the most impacted sector as it may lose its added value. As mentioned above, other companies (even startups) could take over in code development and relegate a production-only task to this sector. The level of fragmentation of the quantum supply chain will dictate how much chemical and pharmaceutical companies will need to maintain numerous collaborations.

Similarly, other sectors that are not purely chemical but are strongly interested in the development of new substances and materials, such as the automotive sector, could develop the necessary substances themselves, without requiring the services of chemical companies and shortening the supply chain.

Resources

Considering the new resources that companies need, there is QaaS cloud service, new materials for their production process (in some cases these resources could be produced internally), and new human capital. The latter will have to be developed internally through a process of up-skilling and in some cases re-skilling or sought in the market.

To protect the development of one's own application and algorithmic production, patents may be needed and become a key resource. Patents clash with the open-source ecosystem that is currently being created: it will only become clear in the future how these two forces will balance each other, whether an open-source or a closed and protective approach will prevail.

The ability to optimise processes allows a more reasoned and efficient use of one's own resources, whether they are acquired from outside or produced internally, with repercussions on both costs and the external environment.

Internal processes

Progress in the field of optimisation will certainly have an impact in all companies in all sectors and in any company block. In particular, optimisation using quantum systems will lead to substantial efficiency gains in internal processes, especially production processes, both in terms of productivity and cost savings, as well as sustainability.

The most impacted internal processes will be R&D for the chemical-pharmaceutical sector and Risk Management, especially for the financial sector. Another strongly impacted process will be logistics, where there are already numerous use cases of path optimisation and logistics optimisation.

External processes

External processes will have a limited impact and will mainly concern the optimisation of product distribution.

Products

On the product side, there will be potentially disruptive opportunities in the chemical-pharmaceutical sector, with the possibility of offering personalised medicines, new materials, new fertilisers, and new fuels. The real potential is still unknown, but the development of new products represents the greatest value for a quantum advantage architecture.
Financial services could offer their risk management, portfolio optimisation and fraud-prediction algorithms to other financial institutions, thus becoming real code developers.

A cross-industry service, which concerns more the logistics sector, is the possibility of offering optimisation applications (e.g., airplane scheduling optimisation) to other companies.

Finally, process optimisation and the use of better performing materials would help the production of higher quality, higher performing, more durable products with a higher rate of customisation.

Customers

The building block relating to customer segments is among the least impacted. The production of new substances, on the chemical side, would lead these companies to extend their customer portfolio or increase their presence in sectors such as consumer goods. Another interesting implication could be the possibility to create highly targeted and personalised products and services by optimising the large amount of consumer data. In this sense, also Quantum Machine Learning could have a relevant impact for the possibilities to clustering and discovering pattern in great amount of data.

Society

Society may be impacted in several ways. It may have great benefits with respect to geopolitical issues: the autonomous creation of substances, such as rare earths, would decrease the need to force international relations for the procurement of these essential raw materials. Further, the production of medicines tailored to the clinical history of patients would improve the health, wellbeing, and lifestyle of many people.

In terms of environmental sustainability, the most visible impact would be in the optimisation of resources and the development of new compounds that could help the food industry to produce high quality products at low cost, with a low environmental impact.

Lastly, as mentioned before, the social paradigm shift towards an open-source collaborative model is an unknown: at the moment, this paradigm is emerging, but it could be due solely to the low level of maturity of the technology.

Costs & revenues

If it is still too early to hypothesise the impact of revenues, more can be said about the cost structure. If on the hardware side one does not expect a high cost for its use in the cloud, the development of skills seems to be the most delicate issue. The paradigm

imposed by quantum computing necessitates a major investment in seeking out existing skills in the labour market and, above all, in developing them in-house.
Finally, there is a cost benefit in optimising both internal and external processes.

Table of impacts on individual building blocks

Building block	**Impacts**	**Sectors Involved (in descending order of impact)**	**Impact value**
Suppliers	I. QaaS II. Partnership ecosystem development III. Increased need for suppliers IV. Autonomous creation of materials	Customer sectors of chemical and pharma companies Chemical/ pharmaceutical sector All industries	Middle
Resources	I. QaaS II. New products III. Autonomous creation of materials IV. Finding expertise in the market	All industries	High

	V. Internal development of new skills VI. Greater sustainability efficiency VII. Patents		
Internal processes	I. Greater efficiency in all internal and external processes II. New processes III. More attention to risk management IV. Greater sustainability efficiency	All industries	High
External processes	I. Greater efficiency in all internal and external processes	Sectors interested in the physical distribution of their products	Low
Products	I. New products	Chemical/ pharmaceutical	High

	II. New services III. Greater efficiency in all internal and external processes	sector Financial sector All industries	
Customers	I. New customer segments II. Greater efficiency in all internal and external processes	All industries Financial sector	Low
Society	I. Autonomous creation of material II. New products & services III. Development of an open-source ecosystem	Chemical industry All industries	Middle
Value proposition	n.d.	n.d.	n.d.

Costs & Revenues	I. QaaS II. Internal development of new skills III. Greater efficiency in all internal and external processes	All industries	Middle

This analysis shows that the most impacted building blocks are "Resources" and "Internal processes". Resources are impacted at 360 degrees as they include changes in physical resources (e.g., new raw materials), intellectual resources (e.g., patents of quantum algorithms) and human resources (e.g., new quantum skills development). These impacts can be considered to affect all sectors, although some are more affected than others.

Quantum computing will also play a key role in internal processes. Its potential in terms of optimisation can achieve new levels of efficiency of all internal processes, especially for those manufacturing companies where the production chain is quite complex.

The building block of new products and services, at the moment, seems to concern some specific industries such as chemical-pharmaceutical and financial sectors. It is not yet clear how other industries might develop new products or services. Considering quantum optimisation, this could relate any company that develops valuable quantum algorithms in-house. These company could externalize them, in a sort of Optimization-as-a-Service.

Summary table of quantum computing impact value per building block

Building block	**Impact value**
Suppliers	Middle

Resources	High
Internal processes	High
External processes	Low
Products	High
Customers	Low
Society	Middle
Value proposition	n.d.
Costs & Revenues	Middle

The analysis shows how companies will potentially be transformed and impacted by quantum computing, in every firm building block. Companies, that have not yet entered the quantum race, should start experimenting and implementing POCs in order not to fall behind, and rather gain the competitive advantage promoted by quantum computing.

"Today, the probability of bringing up quantum computing in any discussion about any computing problem is close to one."

Chris Retford, Google Data Engineer[49]

[49] Source: https://towardsdatascience.com/should-i-already-learn-quantum-computing-953813797d71

Conclusions

The objective of this work was to develop a comparison between quantum computing technology and business models of companies, without focusing on a specific industry.

The analysis, through the papers of consulting firms, research at the Observatory, interviews, and contributions of experts, has led to identify the most impacted sectors. The chemical, pharmaceutical and financial industries are the ones that are most awaited from the market, and they are the industries that expect most from quantum computing. The prospect of being able to develop innovative materials and revolutionary drugs in much less time than current methods represents an important "game-changer" for businesses, customers, and society.

Other areas are not to be underestimated either. Other than simulation, quantum optimization and quantum machine learning are two cross-industry computational approaches. Although experts choose not to define these two approaches as "disruptive", it is undeniable, as expressed in this paper, how much they will be relevant in any business context.

From the point of view of the business models analysis, the work has identified those business areas that will potentially be most impacted. The fact that the analysis was not supported by the literature is an indicator that we are still at a premature stage for the depth of development desired. Only once an architecture with more logical qubits has been obtained, it will be possible to evaluate with greater certainty the impact on companies.

Expert contributions, however, have enhanced and supported this analysis. Few of them unbalanced on how quantum computing might impact one building block rather than another. Discussions turned at a higher level, due to the motivated risk of saying inaccuracies. The responses were very mixed and did not allow for a comprehensive answer to the question of my thesis. In any case, trying to extract as much information as possible from their words, the model obtained can be considered realistic and plausible, as well as a starting point for further studies.

Indeed, I believe that this work could be the starting point for a more in-depth analysis in the coming years. The collection of more data and interviews, the structuring of standard questionnaires, the enlargement of the audience of contributors, the deepening of research and literature are all development points that can be realised in the coming years. Anyway, the paper represents an overview, a handbook for all those who are neophytes for quantum computing and who may be interested in its business positioning.

Every company and manager will soon have to deal with quantum technologies and, in particular, with quantum computing. Despite the doubts on the architecture and the temporal distance of development of a universal quantum computer, it's important to underline that companies already have to develop knowledge on the subject, in order not to remain unprepared for the next years.

It is not a question of "if" it will arrive, but "when".

And perhaps sooner than everyone can imagine.

Appendix A - other relevant use cases

Ford - Road traffic allocation

State: Research & PoC Year: 2019 Industry: Automotive Purpose: Optimization – Routing Problem

Ford Motor Company partnered with Microsoft using "quantum-inspired" technology to test a traffic routing algorithm. They worked together to significantly reduce both congestion and travel time versus the routing recommendations from Bing Maps.

Preliminary studies with up to 5,000 vehicles show more than a 70% decrease in congestion, as well as a reduction of average travel time of approximately 8% (compared to the best routes provided by Bing Maps).

While traffic optimizations of approximately 400 vehicles takes 20 seconds on a quantum annealing machine, Microsoft quantum-inspired algorithms tackle a comparable problem in 0.02 seconds on a single core.

OTI Lumionics - Material Design

State: Research & PoC Year: 2020 Industry: Electronics Purpose: Simulation - Molecular Dynamic Simulation

OTI Lumionics, leader in the development of innovative materials, has developed a project with Microsoft for material design, tailored to OLEDs and other electronic materials.

Instead of using a traditional approach that requires synthesizing and testing thousands of variations to find the right candidate, OTI has developed software to simulate and predict the properties of new materials using Microsoft Azure Quantum optimization tools. With the project, OTI successfully performed a complete simulation of the interaction of the active space configuration of an archetypal OLED material that emits green light.

Total - Energy Resource Optimization

State: Research & PoC Year: 2020 Industry: Energy Objective: Optimization - Resource Allocation Problem

QC Ware and Total, one of the largest energy companies in the world, have announced a joint research collaboration to explore quantum optimization algorithms for Energy Resource Optimization.

The two companies worked together focusing on the potential of quantum computing to model continuous variables to execute optimization use cases (that are critical to Total's operations). The project uses Forge, QC Ware's cloud services platform, which offers a wide range of algorithms.

Delta Airlines - Routing Optimization

State: Research & PoC Year: 2020 Industry: Aerospace Purpose: Optimization - Routing Problem

IBM and Delta Air Lines, leading US airline, have announced multi-year joint research to explore the potential capabilities of quantum computing to transform customer experience in terms of routing optimization.

The airline uses IBM's quantum technology because a large number of variables are involved.

The research focuses on redirecting flights in the event of a delay to minimize the impact on travellers. In addition, with the support of the IBM quantum computer, Delta Air Lines is interested in using biometric technology in its international terminals to improve the customer experience.

BBVA - Monte Carlo Simulation

State: Research & PoC Year: 2020 Industry: Finance Purpose: Monte Carlo Simulation

The BBVA Corporate and Investment Banking (CIB) have announced a joint research collaboration with the US startup Zapata Computing.

They have launched a PoC to evaluate the use of quantum algorithms applied to the Monte Carlo method to determine the price of a derivative instrument. The goal of the test is to investigate whether there are any benefits to using these techniques, what computational resources would be needed to achieve the improvement, and how the results fit the size of the problem.

Netramark - Drug Discovery

State: Research & PoC Year: 2019 Industry: Chemistry Purpose: Simulation - Molecular Dynamics Simulation

NetraMark, an AI company with dedicated solutions for pharmaceutical companies, is working with D-Wave on drug discovery.
The ability to understand a disease through various genetic signatures of its constituent patient population permits to target specific subpopulations. By identifying which specific proteins to target to produce a therapeutic effect, they are helping to enhance personalized medicine. Once this is done, it will be possible to discover molecules that

could be used to heal or treat very serious complex diseases such as certain types of cancer and Alzheimer's disease.

Air Force Research - Path Optimization

State: Research & PoC Year: 2021 Industry: Aerospace Purpose: Optimization - Routing Problem

The Air Force Research Laboratory (AFRL), the United States air force laboratory, and QC Ware are exploring the use of one of QC Ware's proprietary QML algorithms to understand the purpose of the unmanned aircraft mission by observing its flight path.

QC Ware will design and deliver quantum algorithms that can classify the flight plans much faster than the classic machine learning algorithms. The algorithms will be tested with real data in quantum computing hardware, with the aim of determining how many qubits are required for the system to function properly.

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"On the one hand, there are more ideas to test than all traditional experiments that we will be ever able to perform. And yet, ever-growing computing power combined with massive data is starting a novel era of scientific experimentations.

Maybe, we can envision a future where we may solve complex problems without having an extensive hypothesis about the results.

If that will ever be the case, quantum computing might very well accelerate the burial of the scientific method."

Unknown