Quantum Vs Classical Computing: a Comparative Analysis

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***Abstract*—Despite the significant technological advancements, the amount of data to be processed remains enormous, and certain problems remain unsolved or take millions of years to be solved. The advent of quantum computing, with its unique properties, represents a pivotal point in the technological world. Although quantum computers are still under development in the laboratories, research is progressing in parallel with the aim of creating a good basis for any contribution in order to be ready for the commercialization of the first computer. This article clarifies the essential basics required before entering the quantum realm. We present the basic properties of quantum computing based on four fondations and their differences from classical computing.**

***Index Terms*—Quantum Computing, quantum algorithmic, quantum networking, quantum programming, quantum databases, qubits.**

I. Introduction

Computers have been in continuous development since their inception. And this has been supported by Moor's law [1], which states that the number of transistors in a dense integrated circuit (IC) doubles about every two years, doubling computing capacity [2]. However, this theory is no longer valid, because transistors have reached the limit of their size, which tends to the size of an atom and thus, we are now confronted to physics.

Quantum computing is a paradigm that goes beyond the constraints of mechanics. It is based on quantum physics and, due to particular qualities such as entanglement and superposition, it allows to considerably exceed the computation performance of present computers, and even solve issues that are currently unsolved.

This new computing will undoubtedly have a significant impact on growth and industry. Nevertheless, quantum computers are immature and it will take years before they are able to address complex problems, which are currently unsolved by classical computers. When we talk about a new computer science, we think about the fondations on which it is built. That we find in any computer science learning program (with a non-exhaustive list), that every individual in the field must have an idea of. In this article we focus on four foundations that we believe are essential. We note that the article deals with four fondations, which are not treated in a single article in the literature. Through this article we ask how is the algorithmic, the networks, the programming, and the databases, in the quantum world? And what is the difference between these fondations in the classical world and the quantum world? There are reviews in the literature that cover each point independently, but there are no reviews that present the four fondations at once and in a clear form, that answers the issues posed beforehand.

The proposed review aims to provide an outlook on the four fondations in order to clarify these points, enrich the existing surveys in the literature, and provide people interested in the field (research/industry) with a comprehensive study.

The rest of the article is structured as follows: Section 2 provides background information on quantum computing as well as basic features. Section 3 will be devoted to the presentation of the fondations. an overview of the concept in the quantum world based on the existing publications and books in the literature. We have also summarized some contributions for each fondation, the selected articles present the most recent solutions carrying ideas that we consider relevant. Finally, we have presented statistics on the number of publications. For the statistics we used four databases: IEEE Xplore, Springer Link, Science direct and ACM. We have chosen the databases which are classified in the Web of Science Master Journal List [3]. We should point out that the statistics are the result of a primitive statistical analysis. Furthermore, the four databases do not have the same search filters. Section 4 discusses the differences between a quantum and a classical system. Finally, section 5 discusses how a quantum computer works with a classical computer. And we end our article with a conclusion.

II. Background

Quantum computing uses subatomic particle physics to perform complex parallel calculations instead of the simple transistors used in current computer systems.

Traditional computer bits have binary values of 1 or 0. Quantum computers use qubits for computation. A qubit is a unit of operation and can exist as 1, 0 or any other value between them. Mathematically a qubit can be represented as $\alpha|0\rangle+\beta|1\rangle$ where α and β are coefficients which allow mixing or be in an intermediate state of '0' and '1' states. The ability of a qubit to remain in an intermediate state is called ”superposition” [4]. If we have a large number of qubits, we can store them in a register. Quantum computers work by manipulating the qubits in a quantum register.

When we talk about quantum computing, we are referring to whole new features that are unique to the quantum universe. In what follows, we describe the key features that are the source of quantum computing’s strength :

A. Superposition : The particularity of the quantum computing compared to the classical computing, that we will be able to have not only a 0 or 1, but the two situations at the same time. This phenomenon is called the superposition, and that makes the secret of the speed of the quantum computers. In mathematical terms, superposition can be thought of as an equation that has more than one solution. When we solve $x^2 = 4$, x can either be 2 or –2. Both answers are correct. Superposed wave functions will be more complicated to solve, but they can be approached with the same mindset. For example, when a qubit is in a superposition state of equal weights, a measurement will make it collapse to one of its two basis states $|0\rangle$ and $|1\rangle$ with an equal probability of 50%. A quantum computer consisting of n qubits can exist in a superposition of *2n* states: from $|000...0\rangle$ to $|111...1\rangle$. With the information stored in superposition, some problems can be solved exponentially faster [5].

B. Non cloning theorem: The copy in a computer system is a very important functionality. Thanks to it, we create backup to ensure availability which is an important axis in security. In quantum computing, making an identical copy of an element, is not possible owing to the non-cloning theorem. The non-cloning theorem indicates that an unknown quantum state will never be cloned perfectly [6]. Although the non-cloning theorem presents an obstacle in comparison with classical computer science. On the other hand it presents a great advantage for quantum cryptography by preventing the theft of keys by a third person [7].

C. Entanglement: Quantum entanglement is the state where two systems are so strongly correlated, that gaining information about one system will give immediate information about the other. No matter how far apart these systems are [8].
Entanglement does not allow the transmission of classical information faster than the speed of light [9]. Its applications in the field of quantum computing are many, including computation acceleration (exponential/quadratic), solving optimization problems, secure the communication of information over large distances, design of reliable, fast and efficient quantum algorithms, quantum information processing, and quantum internet [8].

D. Teleportation: Quantum teleportation is a completely new way of communicating. What it transmits is no more a classical information, but a quantum information carried by the quantum state, with the help of the quantum entanglement. It should be noted that quantum teleportation does not transmit any matter or energy. Such techniques are very useful in quantum information and quantum computing. However, this method cannot transmit traditional information, so it cannot be used for faster-than-light communication. Quantum teleportation has nothing to do with what is commonly known as teleportation. Quantum teleportation cannot transmit the system itself, nor can be used to organize molecules to form objects [10].

III. The Four Fondations and Their Difference with Classical Computing

The quantum computing is a new approach of computerization. Nevertheless, it assures the same fondations known in the classic computer science: Algorithm, network, programming and database but certainly they follow the laws of the quantum physics.

A. Quantum algorithmic

We cannot talk about computer science without talking about algorithmic and the usual functions: Searching, sorting, basic calculation...etc. With the advent of quantum computing a new mode of problem solving has appeared which is quantum algorithmic.
Quantum algorithm is rapidly evolving and beginning to integrate in the fields of application [11]. A certain number of basic algorithms are known (shor’s algorithm [12], Grover’s algorithm [13], Deutsch-Josza’s oracle [14] etc), and from them researches have started [15] The main difference between quantum algorithmic and classical algorithmic is the complexity and the ability to solve hard problems in a finite time, like factorization [16]. The current research on algorithmic is focused on complex problems [17] that have no solution yet because of the limit of the computing power, and nowadays we talk about the hybrid algorithmic [18].

After developing an algorithmic solution, the complexity of the algorithm must be calculated; the complexity of an algorithm is related to how the algorithm evolves in response to data. In quantum computing we talk about the sub-discipline quantum complexity [19], where we distinguish the class BQP (Bounded error Quantum Polynomial time), which is the class of the algorithms solved with a quantum computer, it includes a part of the algorithms of the class NP, we also find QMA (Quantum Merlin Arthur) which is the equivalent of the class NP in classical computing. The current hypothesis is that NP-Complete and BQP are disjoint sets. This means that any NP-Hard problem would always be difficult for a quantum computer [20].

Figure 1 shows the number of articles related to quantum algorithm found with the keyword ”quantum algorithm” between the years 1995-2022.

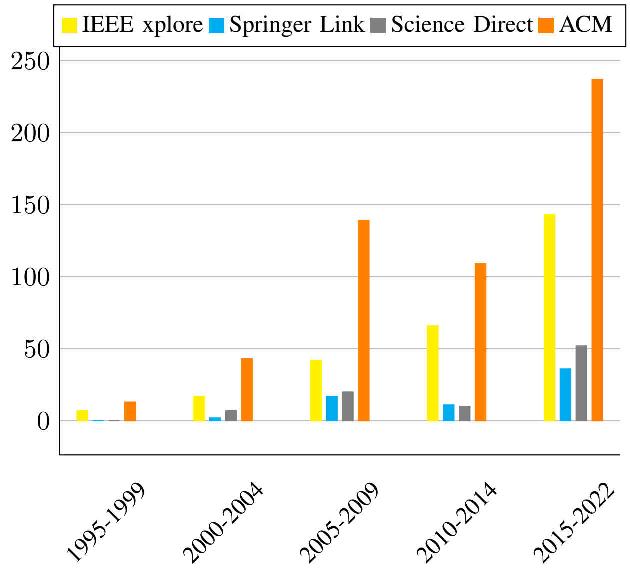

Fig. 1: Quantum algorithmic's publications

In the following, we summarize some works in quantum algorithmics :

- [11] : Portugal, Renato,2022, provided a detailed explanation of the most crucial algorithms. In addition, they provide a description of the quantum circuit.
- [12] : Ekert et al.,1996, presented Shor's algorithm, as well as an introduction to quantum computing and complexity theory. They also analyzed experiments that could assist in its implementation.
- [17] : Atchade-Adelomou and Parfait, analysed how quantum computers can solve hard weekly tasks, such as determining the ideal schedule for social workers and determining a robot's trajectory.
- [21] : Liu, Chang;,2020, the authors propose a quantum algorithm for single-source shortest path search, for weighted directed acyclic graphs (DAG), with improved complexity compared to a previously proposed algorithm.

B. Quantum networking

The Institute of Electrical and Electronics Engineers (IEEE) defines a network as follows: It is a data communication scheme that allows several independent devices to communicate directly with each other over moderately fast physical communication channels within a suitable area. Quantum networks are like the classical networks used to transmit and share digital information in our daily lives. However, quantum networks use quantum bits, or qubits, to encode information in a completely different way than classical thinking [22]. We can employ entangled qubits to get instantaneous information exchange over very great distances. [8], Remote nodes having stationary qubits or quantum memory in quantum networks must be linked by flying qubits, such as single photons[1]. Photons at telecommunication wavelengths offer minimum loss in fiber networks for long-distance transmission, the quantum state of each entangled photons [23] is correlated with that of its entangled partners regardless of their distance apart.
To create large-scale quantum computer networks, researchers need to develop devices that can amplify the signals that these networks will carry. Quantum repeaters would create multiple entangled pairs of qubits, that would ling together to form a giant entangled chain [24]. True quantum repeaters have not been realized yet [25],but lab experiments have already begun to show key functions that will be needed for entanglement-based quantum networks [26].

[1]photons are the smallest possible packets of electromagnetic energy

Figure 2 shows the number of articles related to quantum network found with the keyword ”quantum network” between the years 1995-2022.

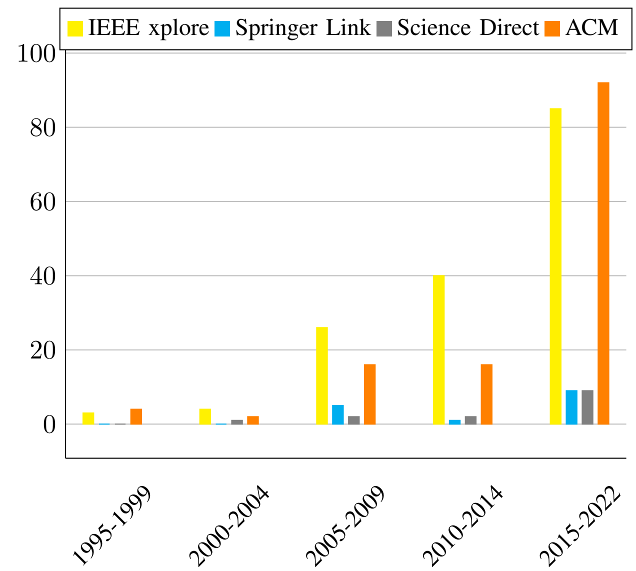

Fig. 2: Quantum network's publications

In the following, we summarize some works in quantum networking :

- [27] : Kozlowski et al.,2020, proposed a quantum data plane network protocol. That will be in charge of coordinating, generating, link-level entanglement, and subsequent entanglement exchange along a path between two remote nodes, while avoiding and compensating for decoherence losses. The protocol requires at least two external services: a signaling protocol and a routing protocol.
- [28] : Munro et al.,2021, described an aggregation approach. It allows the utilization of numerous channels. Each one consists of many communication channels, and having a variable probability of success for the transmission of a photon. To meet a level of reliability established at the beginning.
- [29] : Pant et al.,2019, proposed entanglement routing protocols provide instructions to nodes, on how to dy-

namically choose which BSMs (Bell state measurement, also known as entanglement swapping), to perform at each time interval. In order to maximize the entanglement generation rate for a set of entanglement flows, based on the network topology, end user location, and current knowledge of the link state.
- [30] : Kelley et al.,2016, proposed a quantum network security framework, for the cloud. This framework enables the teleportation of quantum information between the source and destination. In order to authenticate an application running as a root in the daemon and the host.

C. Quantum programming

Programming refers to the work of creating a program. A program is a set of instructions related to a computer. These programs come together to form a software. The tool used to create such software is called a "programming language" which is the intermediate language between the computer and the human being.
Majority of programming languages support both syntactic and semantic form..
In the quantum world, the definition remains the same except that the language and tools change to accommodate the quantum nature.
A quantum program is a combination of classical code blocks and quantum components. Therefore, a typical quantum program contains two types of instructions, namely quantum instructions (an ordered sequence of quantum gates, measurements and resets, called a quantum circuit) and classical instructions. [31].

Figure 3 shows the number of articles related to quantum programming found with the keyword "quantum programming" between the years 1995-2022.

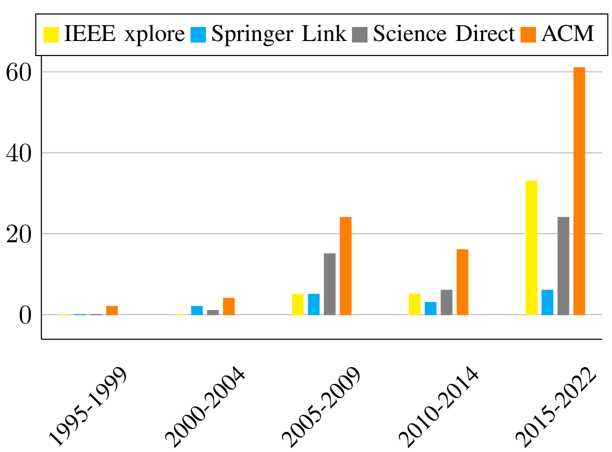

Fig. 3: Quantum programming's publications

In the following, we summarize some works in quantum programming :
- [32] : Da Rosa et al.,2021, presented a proposal for an execution architecture, allowing a dynamic interaction between classical and quantum computers. This proposal has been validated by the implementation of the Ket frameworek. Using Ket and a single programming language we obtain a separable quantum and classical code/execution.
- [33] : Das et al.,2019, provided three ways to multi-program in NISQ (Noisy Intermediate Scale Quantum) machines.Which will improve exploitation and guarantee the accuracy of the results.
- [34] : De Stefano et al.,2022, gathered all GitHub repositories, that uses the most popular quantum programming frameworks today. A taxonomy of quantum programming challenges, a survey of contributors to the reviewed repositories, and developers' perspectives on the acceptance and challenges of quantum programming today.

D. Quantum database

Charles Bachmann introduced the concept of database in 1960 [35]. The main purpose was to store data to be able to consult/modify them later. Currently, we talk about Big Data due to the immense amount of existing data. Access and management of these latter has become expensive and requires a high speed of calculation. quantum computers can handle big data [36].

In a quantum database, the data are represented as quantum circuits where each circuit corresponds to a table in a relational model [37]. In order to query a database, we need an adequate language, hence we find the QQL language (quantum query language) [38] which allows to launch the basic queries (tests were carried out on prototypes) which are :
- **Select :** is used to retrieve information selected by the user, Younes proposes an equation ,in [39], based on entanglement. The searched elements are entangled with the state $|1\rangle$ and the bad ones with the state $|0\rangle$. So far, This can be considered as the SELECT operator since the selected states are entangled with the state $|1\rangle$.
- **Update :** is used to modify or update values according to a specific condition, Younes in [39] proposes the update without touching the amplitude of the data, in other words make a permutation. This permutation can be represented by the CNOT operator; the CNOT gate operates on a quantum register consisting of 2 qubits. The CNOT gate flips the second qubit (the target qubit). If and only if the first qubit (the control qubit) is $|1\rangle$).
- **Insert :** is an operation which serves to add a new value in a given base, Younes in [39] proposes the superposition. Controlled Hadamard gates can be used to input a given number of records r to a superposition while only allowing one record to be inserted at a time.
- **Delete :** is to remove an element from a database, a subset can be defined for deletion using a condition. Until now there has been no solution to delete from a quantum

database. Younes proposes a method based on a Boolean function in [39] which cannot yet be applied in reality.

Finally, Sudip Roy, Lucja Kot and Christoph Koch in [40] present more details on quantum databases with experiments and analysis of the results using prototypes.

Figure 4 shows the number of articles related to quantum database found with the keyword "quantum database" between the years 1995-2022.

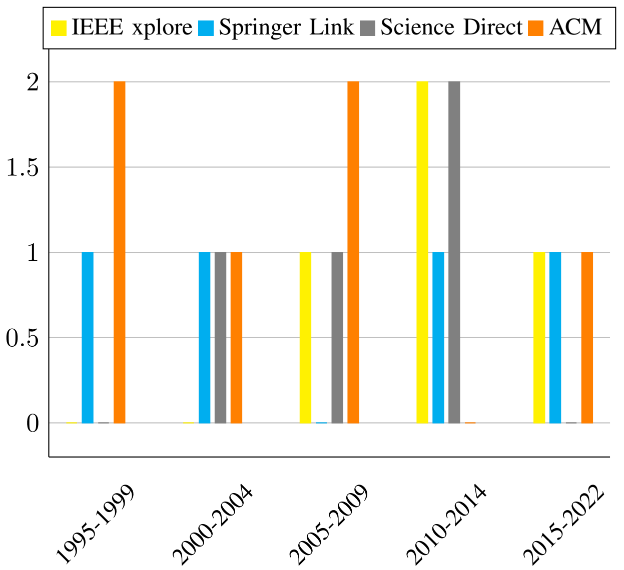

Fig. 4: Quantum database's publications

In the following, we summarize some works in quantum database :

- [41] : Yang et al.,2019, proposed a new d-dimensional quantum protocol (the d-dimensional protocol allows the user to query multi-bit block, with length no more than logd from the database, via only one query) for private database querying (the query is unknown to the database owner, and the user can retrieve an n-bit message element, without knowing any additional information). The proposed protocol eliminates both the d-dimension and restriction and allows users to obtain messages of arbitrary length, thus reducing the communication complexity. The security of the proposed protocol in the zero error situation has been proven.
- [42] : Yan et al.,2020, presented a semi-quantum private query technique. It uses just single photons. And does not require quantum memory (the user can retrieve an item at once). The protocol is resistant to external eavesdropping attacks, and preserves the database and its owner's privacy. In a real-world application, the protocol is subject to Trojan horse assaults.
- [38] : Gueddana et al.,2014, proposed a complete design of a multi-table relational database. As well as a procedure for converting any multi-table RDB (relational database) into a QRDB (quantum relational database), and finally, how to execute basic and advanced queries, to manipulate records in simple or joined digitized tables.

E. Diffrences with classical computing

After the presentation of each fondations, the main differences are summarized in Fig.5, we present a simple comparison of the four fondations (algorithmic, network, programming, and database) in the quantum and classical worlds, while mentioning the fondations' purpose, which is the same in both paradigms, that can be exploited to promote cooperation between the two systems and produce future hybrid environments [43].

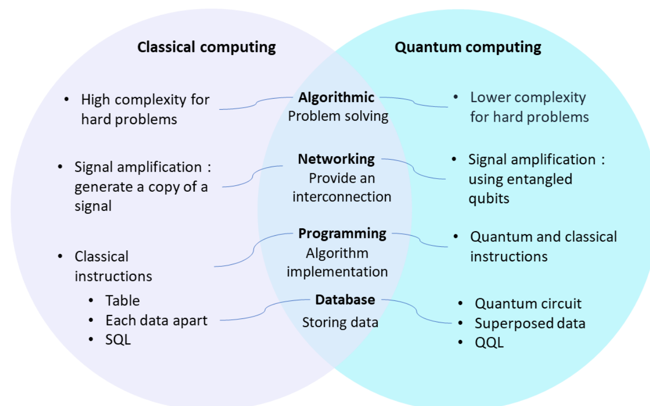

Fig. 5: The classical and quantum side of the four fondations

F. Research trends

The potential of employing quantum algorithms to tackle unsolved problems motivates a significant portion of interest in quantum computers. The present difficulty for algorithmic, is to be able to shift from purely theoretical algorithms to a program understandable by programming languages. Researchers, on the other hand, do not yet know how an algorithm will work on a real quantum machine [44]. This topic still requires additional research. In order to provide solutions to problems that are waiting in the classical world, due to the computational limit.

Quantum networks are currently only experiments in research laboratories. Nonetheless, efforts are being made to develop long-distance networks. Protocols to ensure communication are suggested and tested on simulators [45]. Furthermore, communication between a classical and quantum system will be required in the future. Nanni and his colleagues are developing a chip that will act as an interface between the two systems [46]. Finally, a quantum internet, the concept that aims to allow communication between any two points on earth, is under research [47].

There are various tools and platforms for quantum programming that uses high-level languages. Despite its progress in comparison to other fondations, this field faces numerous challenges. Scalability of programs is a big difficulty, because programs produced today are constrained by the amount of qubits accessible. Furthermore, for the same fault in a classical program, the same solution is applicable, but in the quantum world, different procedure must be employed, since a quantum system is a probabilistic system [48]. A quantum program is always susceptible to error, especially if a high number of qubits are used. Consequently, the trend is towards multi-programming, which allows a better exploitation of resources while using the same number of qubits [49].

A significant challenge is storing a vast amount of data (big data) and then conducting : searches, insertions, updates, and deletions in an optimal time [50]. However, research towards query languages is ongoing [38]. Additionally, the security of information search in a quantum database is a significant challenge. Each person must have access only to the data to which he is permitted (database confidentiality and integrity); the database owner must ensure that the information is available at the moment of the request (availability). Furthermore, the database owner must not have access to the requested data (user confidentiality).

IV. Quantum computing vs classical computing

Quantum computing represents a fundamentally new paradigm in software and hardware. The ultimate goal, however, remains the same as in classical computing: to execute calculations faster than contemporary supercomputers. Or even to address problems that have gone unresolved due to a lack of processing capacity. As a result, quantum computing is employed for sophisticated and time-consuming processes such as data processing and factorization. Because of the expensive cost of quantum technology and the onerous circumstances of implementation, conventional computing is employed for everyday tasks. Definitely, quantum computing is based on quantum theory, which describes the behaviour of microscopic particles, whereas Albert Einstein's theory of relativity, which traditional computers now follow, describes the behaviour of macroscopic entities. Data will be processed by quantum computers employing microscopic particles or other incredibly small objects. These objects are sensitive to any noise or decoherence, which poses a problem for reliable execution.

There have been multiple studies that compare quantum and classical computing from various perspectives. As a result, we decided to contribute to the literature and compare the two paradigms by specifying key fondations. A.V.Navaneeth and Marichi R. Dileep in [51] investigated how to address problems that exist in both the classical and quantum realms. Bub in [52] conducted a comparison of the classical and quantum methods, as well as their attributes. Le Gall in [53] demonstrated how to obtain exponential spatial complexity separation in quantum and conventional lines.

The following table -TABLE I- summarizes the distinctions between classical and quantum computing.

TABLE I: Quantum VS classical computing

Parameters of comparison	**Quantum Computing**	**Classical Computing**
Basic unit	Qubit	Bit
information storage	N-Qubits holds (2^N) values	N-Bits holds one value(0-2^N)
Error rates	High error rate	Less error rate
Best suitable	Best appropriate for data analysis	Best suitable for the daily processing
Possible states	Continuous	Discrete
Information processing	Using quantum logic gates	Using Logic gates like AND, OR
Operations	Linear algebra	Boolean algebra
Technology	Microscopic	Macroscopic
Operating conditions	Very low temperature, away from radio waves	Natural conditions
Speed evolution	scales exponentially	scales linearly
System results	Probabilistic	Deterministically (0 or 1)
Data	Severe restrictions exist on copying and measuring signals	No restrictions exist on copying or measuring signals

V. How quantum computing will work with classical computer?

We discussed the distinctions between classical and quantum computers in the previous section. However, a hybrid classical-quantum system is needed to exploit the advantages of each system. The high computing capacity of a quantum computer is well recognized. As a result, a traditional computer is still required for daily tasks.
A hybrid architecture has been proposed and detailed in [54], The quantum circuit is divided into classical and quantum circuits. The quantum circuits are evaluated on cloud-based quantum computers, whereas the classical circuits are analysed on a traditional supercomputer. The quantum computer's output will be translated into classical bits and relayed back to the supercomputer. In [43], a group of researchers from Microsoft Research, Columbia University, and ETH Zurich university describe their strategy to develop a hybrid quantum-classical algorithm on small quantum computers for material simulation and development. Based on a hybrid architecture and helped by a framework.
Regarding practical side, Nvidia has released a hybrid simulation platform that combines QPUs (Quantum processing units) and CPUs in a single machine. It provides a programming model based on C++. A Python-based model is under development. It is interoperable with other GPUs (graphics processing units) and provides a common library of quantum computing primitives, among other benefits. This platform aims to accelerate research in the field of quantum algorithms by accelerating hybrid quantum-classical development through the simulation of quantum circuits. [55].
Hybrid quantum-classical computing works today by accessing

quantum systems that are still under development, in research labs, or simulators provided by several manufacturers. It is possible to do this through the cloud and by integrating their capabilities with classical cloud computing. The ultimate goal is to allow the user to no longer need to know or worry about which computer (classical/quantum) is doing what. He will only receive a better result.

VI. Conclusion

Quantum computing is a hot topic, which has the potential to disrupt all disciplines within a few years. But it is necessary to understand the fondations to adapt to this new paradigm. Through this article, we were able to do a review that deals with the basics of quantum computing, based on four fondations: algorithmic, network, programming, and databases. For each fondation, we have mentioned some works, including the number of publications for each concept. Then we have shown each fondation with its particularities in the classical and quantum world. At the end, a comparative table summarizes the differences between the two paradigms. This work improves our understanding of the quantum universe, and paves the way for future reviews to expand the literature, and allow scholars to propose new solutions. Moreover, additional in-depth study may be conducted in the future to continue exploring other aspects of quantum computing and potentially provide solutions to open quantum challenges.

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