# FROM BITS TO QUBITS, FROM COMPUTING TO QUANTUM COMPUTING: AN EVOLUTION ON THE VERGE OF A REVOLUTION IN THE COMPUTING LANDSCAPE

*Alexandru PÎRJAN* [1*]
*Dana-Mihaela PETROŞANU* [2]

## ABSTRACT

*The "Quantum Computing" concept has evolved to a new paradigm in the computing landscape, having the potential to strongly influence the field of computer science and all the fields that make use of information technology. In this paper, we focus first on analysing the special properties of the quantum realm, as a proper hardware implementation of a quantum computing system must take into account these properties. Afterwards, we have analyzed the main hardware components required by a quantum computer, its hardware structure, the most popular technologies for implementing quantum computers, like the trapped ion technology, the one based on superconducting circuits, as well as other emerging technologies. Our study offers important details that should be taken into account in order to complement successfully the classical computer world of bits with the enticing one of qubits.*

**KEYWORDS:** *Quantum Computing, Qubits, Trapped Ion Technology, Superconducting Quantum Circuits, Superposition, Entanglement, Wave-Particle Duality, Quantum Tunnelling*

## 1. INTRODUCTION

The "Quantum Computing" concept has its roots in the "Quantum Mechanics" physics subdomain that specifies the way how incredibly small particles, up to the subatomic level, behave. Starting from this concept, the Quantum Computing has evolved to a new paradigm in the computing landscape. Initially, the concept was put forward in the 1980s as a mean for enhancing the computing capability required to model the way in which quantum physical systems act. Afterwards, in the next decade, the concept has drawn an increased level of interest due to the Shor's algorithm, which, if it had been put into practice using a quantum computing machine, it would have risked decrypting classified data due to the exponential computational speedup potential offered by quantum computing [1].

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[1*] corresponding author, PhD Hab, Professor Faculty of Computer Science for Business Management, Romanian-American University, 1B, Expozitiei Blvd., district 1, code 012101, Bucharest, Romania, E-mail: alex@pirjan.com
[2] PhD Lecturer Department of Mathematics-Informatics, University Politehnica of Bucharest, 313, Splaiul Independentei, district 6, code 060042, Bucharest, Romania, E-mail: danap@mathem.pub.ro

However, as the development of the quantum computing machines was infeasible at the time, the whole concept was only of theoretical value. Nowadays, what was once thought to be solely a theoretical concept, evolved to become a reality in which quantum information bits (entitled "qubits") can be stored and manipulated. Both governmental and private companies alike have an increased interest in leveraging the advantages offered by the huge computational speedup potential provided by the quantum computing techniques in contrast to traditional ones [2].

One of the aspects that make the development of quantum computers attractive consists in the fact that the shrinkage of silicon transistors at the nanometer scale that has been taking place for more than 50 years according to Moore's law begins to draw to a halt, therefore arising the need for an alternate solution [3].

Nevertheless, the most important factor that accounts for boosting the interest in quantum computing is represented by the huge computational power offered by these systems and the fact that their development from both hardware and software perspectives has become a reality. Quantum computing managed to surpass the computability thesis of Church-Turing, which states that for any computing device, its power computation could increase only in a polynomial manner when compared to a "standard" computer, entitled the Turing machine [4].

During the time, hardware companies have designed and launched "classical" computing machines whose processing performance has been improving over the time using two main approaches: firstly, the operations have been accelerated through an increased processing clock frequency and secondly, through an increase in the number of operations performed during each processing clock's cycle [5].

Although the computing processing power has increased substantially after having applied the above-mentioned approaches, the overall gain has remained in accordance with the thesis of Church-Turing. Afterwards, in 1993, Bernstein and Vazirani have published in [6] a theoretical analysis stating that the extended Church-Turing thesis can be surpassed by means of quantum computing. In the following year, Peter Shor has proved in his paper that by means of quantum computing the factorization of a large number can be achieved with an exponentially computing speedup when compared to a classical computing machine [7-9]. Astonishing as the theoretical framework was, a viable hardware implementation was still lacking at the time.

The first steps for solving this issue have been made in 1995, when scientists have laid the foundations for a technology based on a trapped ion system [10] and afterwards, in 1999, for a technology employing superconducting circuits [11]. Based on the advancement of technology, over the last decades, researchers have obtained huge progress in this field, therefore becoming able to build and employ the first quantum computing systems.

While in the case of a classical computing machine the data is stored and processed as bits (having the values 0 or 1), in the case of a quantum computing machine, the basic unit of quantum information under which the data is stored and processed is represented by the quantum bits, or qubits that can have besides the values of 0 and 1, a combination of both these values in the same time, representing a "superposition" of them [12].

At a certain moment in time, the binary values of the *n* bits corresponding to a classical computer define a certain state for it, while in the case of a quantum computer, at a certain moment in time, a number of *n* qubits have the possibility to define all the classical computer's states, therefore covering an exponential increased computational volume. Nevertheless, in order to achieve this, the qubits must be quantum entangled, a non-local property that makes it possible for several qubits to be correlated at a higher level than it was previously possible in classical computing. In this purpose, in order to be able to entangle two or several qubits, a specific controlled environment and special conditions must be met [13].

During the last three decades, a lot of studies have been aiming to advance the state of knowledge in order to attain the special conditions required to build functional quantum computing systems. Nowadays, besides the most popular technologies employed in the development of quantum computing systems, namely the ones based on trapped ion systems and superconducting circuits, a wide range of other alternative approaches are being extensively tested in complex research projects in order to successfully implement qubits and achieve quantum computing [14].

One must take into account the fact that along with the new hardware architectures and implementations of quantum computing systems, new challenges arise from the fact that this new computing landscape necessitates new operations, computing algorithms, specialized software, all of these being different than the ones used in the case of classical computers.

A proper hardware implementation of a quantum computing system must take into account the special properties of the quantum realm. Therefore, this paper focuses first on analyzing these characteristics and afterwards on presenting the main hardware components required by a quantum computer, its hardware structure, the most popular technologies for implementing quantum computers, like the trapped ion technology, the one based on superconducting circuits, as well as other emerging technologies. Our developed research offers important details that should be taken into account in order to complement successfully the classical computer world of bits with the enticing one of qubits.

## 2. SPECIAL PROPERTIES OF THE QUANTUM REALM

The huge processing power of quantum computers results from the capacity of quantum bits to take all the binary values simultaneously but harnessing this vast amount of computational potential is a challenging task due to the special properties of the quantum realm. While some of these special properties bring considerable benefits towards quantum computing, there are others that can hinder the whole process.

One of the most accurate and extensively tested theory that comprehensibly describes our physical world is quantum mechanics. While this theory offers intuitive explanations for large-scale objects, while still very accurate also at the subatomic level, the explanations might seem counterintuitive at the first sight. At the quantum level, an object does not have a certain predefined state, the object can behave like a particle when a measurement is performed upon it and like a wave if left unmeasured, this representing a special quantum property entitled wave-particle duality [15].

The global state of a quantum system is determined by the interference of the multitude of states that the objects can simultaneously have at a quantum level, the state being mathematically described through a wave function. Actually, the system's state is often described by the sum of the different possible states of its components, multiplied by a coefficient consisting in a complex number, representing, for each state, its relative weight [16, 17]. For such a complex coefficient, by taking into consideration its trigonometric (polar) form, one can write it under the form $Ae^{i\theta} = A(cos\theta + i\, sin\theta)$, where $A > 0$ represents the module of this complex number and is denoted as the "amplitude", while $\theta$ represents the argument of the complex number, being denoted as "the phase shift". Therefore, the complex coefficient is known if the two real numbers $A$ and $\theta$ are known.

All the constitutive components of a quantum system have wave-like properties, therefore being considered "coherent". In the case of coherence, the different states of the quantum components interact between them, either in a constructive manner or in a destructive one [1]. If a quantum system is measured at a certain moment, the system exposes only a single component, the probability of this event being equal to the squared absolute value of the corresponding coefficient, multiplied by a constant. If the quantum system is measured, from that moment on it will behave like a classical system, therefore leading to a disruption of its quantum state. This phenomenon causes a loss of information, as the wave function is collapsed, and only a single state remains. As a consequence of the measurement, the wave function associated to the quantum object corresponds only to the measured state [1, 17].

Considering a qubit, one can easily demonstrate that its quantum state could be represented by a linear superposition of two vectors, in a space endowed with a scalar product having the dimension 2. The orthonormal basis in this space consists of the vectors denoted as $|0>=\begin{bmatrix}1\\0\end{bmatrix}$ and $|1>=\begin{bmatrix}0\\1\end{bmatrix}$. If one considers two qubits, they could be represented as a linear combination of the $2^2$ elements of the base, namely the ones denoted as $|00>=\begin{bmatrix}1\\0\\0\\0\end{bmatrix}$, $|01>=\begin{bmatrix}0\\1\\0\\0\end{bmatrix}$, $|10>=\begin{bmatrix}0\\0\\1\\0\end{bmatrix}$, $|11>=\begin{bmatrix}0\\0\\0\\1\end{bmatrix}$. Generally, in the case of $n$ qubits, they could be represented by a superposition state vector in a space having the dimension $2^n$ [2].

Another special property of the quantum realm consists in the entanglement, a property that has the ability to exert a significant influence on quantum computing and open up a plethora of novel applications. The physical phenomenon of quantum entanglement takes place when two (or more) quantum objects are intercorrelated and therefore the state of a quantum object influences instantaneously the state(s) of the other(s) entangled quantum object(s), no matter the distance(s) between these objects [16].

Another important quantum mechanical phenomenon that plays a very important role in quantum computing is quantum tunneling that allows a subatomic particle to go through a potential barrier, which otherwise would have been impossible to achieve, if it were to obey only the physical laws of classical mechanics. An explanation of this different behavior consists in the fact that in quantum mechanics the matter is treated both as waves and particles, as we have described above, when we have presented the wave-particle duality concept [15].

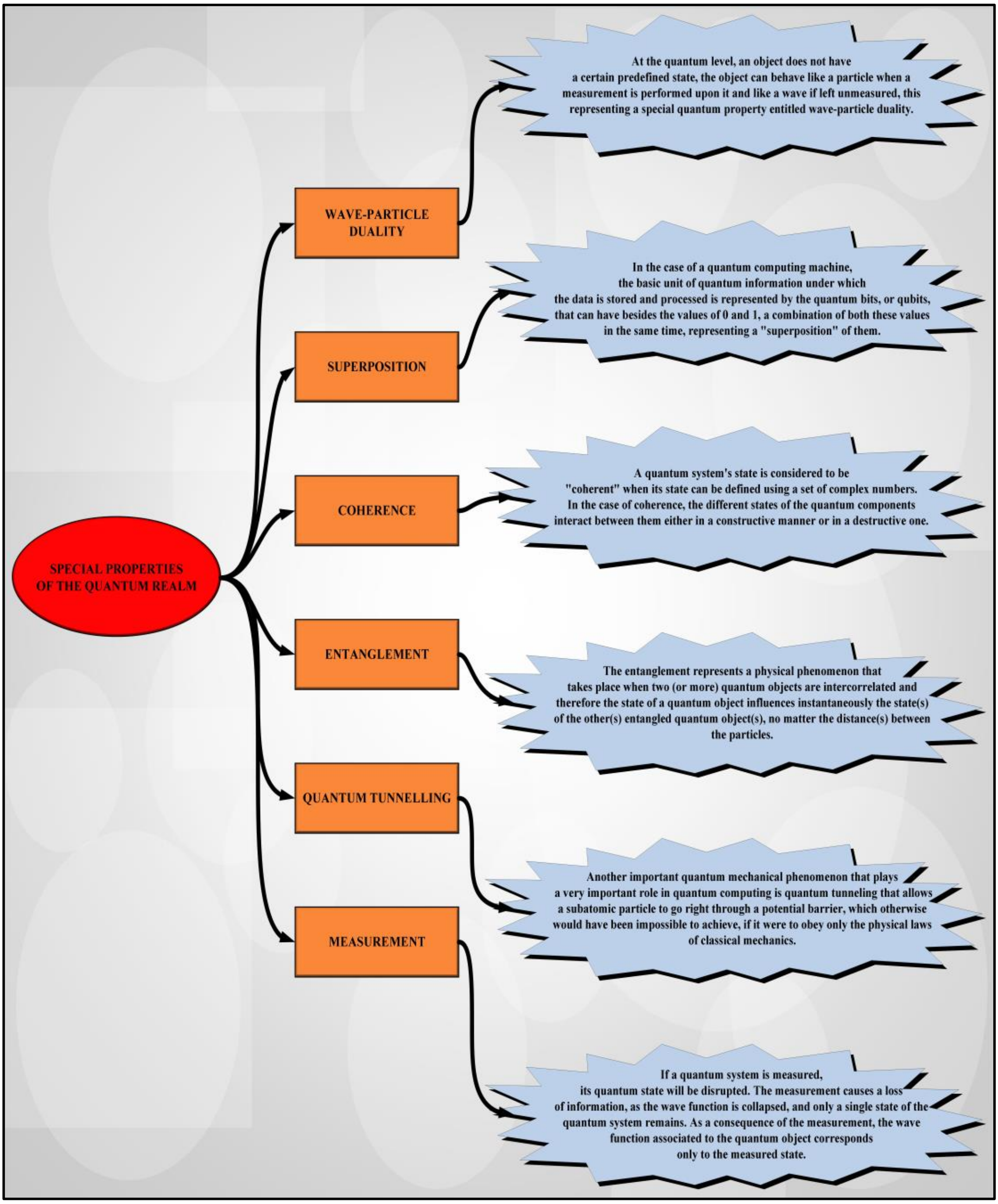


Figure 1. The main special properties of the quantum realm[1]

The Schrödinger equation describes the variation of the wave function, taking into account the energy environment that acts upon a quantum system, therefore highlighting the way in which this quantum system evolves. In order to obtain the mathematical description of the environment, of the energies corresponding to all the forces acting upon

[1] The Figure has been devised using Microsoft Visio, based on the information presented in [1, 12, 15-17].

the system, one uses the Hamiltonian of the quantum system. Therefore, the control of a quantum system can be achieved by controlling its energy environment, which can be obtained by isolating the system from the external forces, and by subjecting the system to certain energy fields as to induce a specific behavior. One should note that a perfect isolation of the quantum system from the external world cannot be achieved, therefore in practice the interactions are minimized as much as possible. Over time, the quantum system is continuously influenced to a small extent by the external environment, through a process called "decoherence", process that modifies the wave function, therefore collapsing it to a certain degree [1].

**Figure 1** depicts the main special properties of the quantum realm, which, when precisely controlled, have the ability to influence to a large extent the performance of a quantum computer implementation, and open up new possibilities for innovation concerning the storing, manipulation and processing of data.

In the following, we analyze a series of hardware components and existing technologies used for developing and implementing quantum computers.

## 3. AN OVERVIEW OF THE NECESSARY HARDWARE AND OF THE EXISTING TECHNOLOGIES USED IN THE IMPLEMENTATIONS OF QUANTUM COMPUTERS

A proper hardware architecture is vital in order to be able to program, manipulate, retrieve qubits and overall to achieve an appropriate and correct quantum computer implementation. When implementing a quantum computer at the hardware level, one must take into account the main hardware functions, a proper modularization of the equipment along with both similarities and differences between quantum and classic computer implementations. Conventional computers are an essential part in the successful implementation of a quantum computer, considering the fact that after having performed its computation, a quantum computer will have to interact with different categories of users, to store or transmit its results using classic computer networks. In order to be efficient, quantum computers need to precisely control the qubits, this being an aspect that can be properly achieved by making use of classic computing systems.

The scientific literature [1, 18, 19] identifies four abstract layers in the conceptual modelling process of quantum computers. The first layer is entitled the "quantum data plane" and it is used for storing the qubits. The second layer, called "control and measurement plane", performs the necessary operations and measurement actions upon the qubits. The third layer entitled "control processor plane" sets up the particular order of operations that need to be performed along with the necessary measurement actions for the algorithms, while the fourth abstract layer, the "host processor", consists in a classical computer that manages the interface with the different categories of personnel, the storage of data and its transmission over the networks.

In the following, we present the two most popular technologies employed in the development of quantum computing systems, namely the ones based on trapped ion systems and superconducting circuits and, afterwards, other alternative approaches that are being extensively tested in complex research projects in order to successfully implement qubits and achieve quantum computing.

By means of trapping atomic ions, based on the theoretical concepts presented by Cirac et al within [20], in 1995, Monroe et al [21] revealed the first quantum logic gate. This was the starting point in implementing the first small scale quantum processing units, making it possible to design and implement a rich variety of basic quantum computing algorithms. However, the challenges to scale up the implementations of quantum computers based on the trapped ion technology are enormous because this process implies a synergy of complex technologies like coherent electronic controllers, laser, radio frequency, vacuum, microwave [1, 22].

In the case of a quantum computer based on the trapped atomic ions technology, the qubits are represented by atomic ions contained within the quantum data plane by a mechanism that keeps them in a certain fixed location. The desired operations and measurement actions are performed upon the qubits using accurate lasers or a source of microwave electromagnetic radiation in order to alter the states of the quantum objects, namely the atomic ions. In order to reduce the velocity of the quantum objects and perform measurements upon them, one uses a laser beam, while for assessing the state of the ions one uses photon detectors [14, 23, 24]. **Figure 2** depicts an implementation of the quantum trapping atomic ions technology.

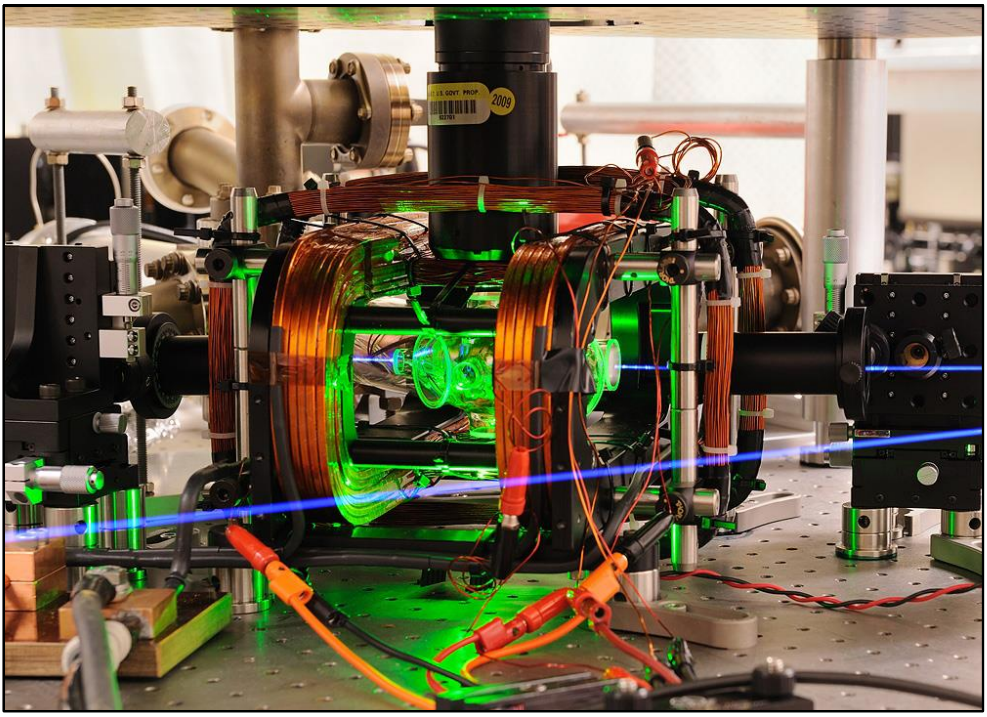


Figure 2. An implementation of the quantum trapping atomic ions technology (the image depicted in this figure is licensed under the public domain, being available for reuse)[1]

[1] https://commons.wikimedia.org/wiki/File:Microwave_Apparatus_(6029992084).jpg

Another popular technology used in the development and implementation of quantum computers is based on superconducting quantum circuits. These quantum circuits have the property of emitting quantized energy when exposed to temperatures of $10^{-3}$K order, being referred in the literature as "superconducting artificial atoms" [25]. In contrast to classic integrated circuits, the superconducting quantum circuits incorporate a distinctive characteristic, namely a "Josephson junction" that uses wires made of superconducting materials in order to achieve a weak connection. The common way of implementing the junction consists in using an insulator that exposes a very thin layer and is created through the Niemeyer–Dolan technique which is a specialized lithographic method that uses thin layers of film in order to achieve overlapping structures having a nanometer size [26].

Superconducting quantum circuits technology poses a series of important advantages, offering reduced decoherence and an improved scale up potential, being compatible with microwaves control circuits, operating with time scales of the nanosecond order [1]. All of these characteristics make the superconducting quantum circuits an attractive and performant technique in developing quantum computers. A superconducting quantum circuit developed by D-Wave Systems Inc. is depicted in **Figure 3.**

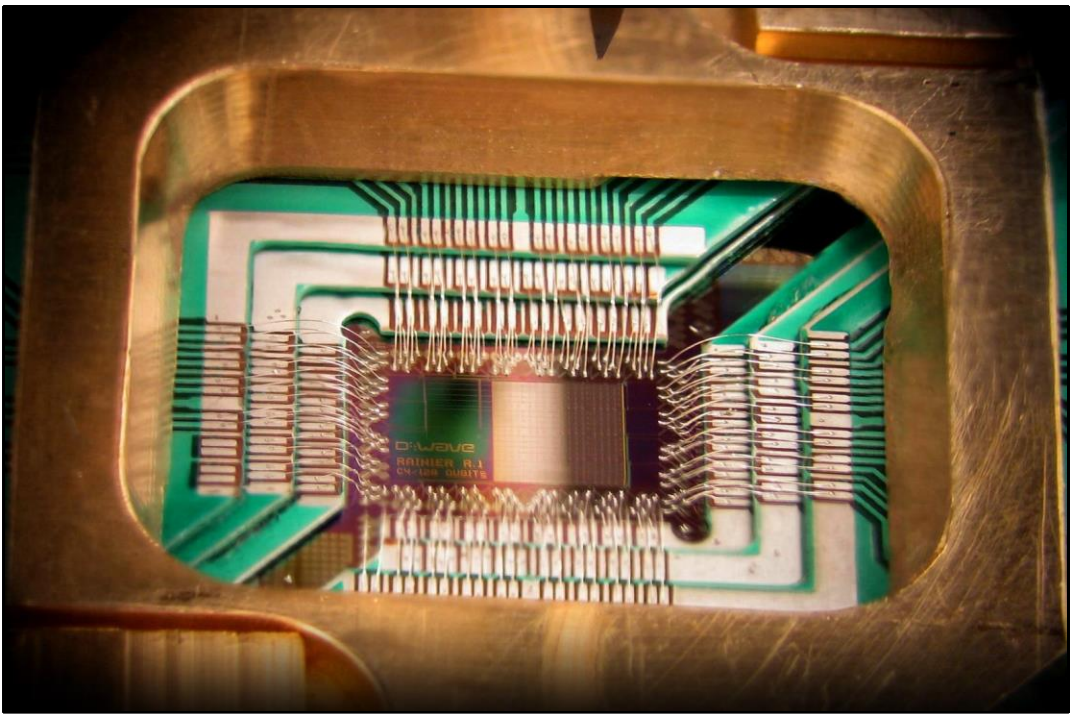


Figure 3. A superconducting quantum circuit developed by D-Wave Systems Inc.
(the image is licensed for reuse under the Creative Commons Attribution 3.0 License)[1]

In order to overcome the numerous challenges regarding the scaling of quantum computers developed based on trapped ion systems and superconducting circuits, many

[1] https://commons.wikimedia.org/wiki/File:DWave_128chip.jpg

scientists focus their research activity on developing emerging technologies that leverage different approaches for developing quantum computers.

One of the alternatives that scientists investigate consists in making use of the photons' properties, especially of the fact that photons have a weak interaction between each other and also with the environment. The photons have been tested in a series of quantum experiments and the obtained results made the researchers remark that the main challenge in developing quantum computers through this approach is to obtain gates that operate on spaces of two qubits, as at the actual moment the photons offer very good results in terms of single qubit gates. In order to obtain the two-qubit gates, two alternative approaches are extensively being investigated as these have provided the most promising results.

The first approach is based on operations and measurements of a single photon, therefore creating a strong interaction, useful in implementing a probabilistic gate that operates on a space of two qubits [1]. The second alternative approach employs semiconductor crystals structures of small dimensions in order to interact with the photons. These small structures can be found in nature, case in which they are called "optically active defects", but can also be artificially created, case in which they are called "quantum dots". An important challenge that must be overcome when analyzing quantum computers based on photons is their size. Until now, the development of this type of computers has been possible only for small dimensions, as a series of factors limit the possibility to increase the dimensions of photon quantum computers: the very small wavelengths of the photons (micron-size), their very high speed (the one of the light), the direction of their movement being along a certain dimension of the optical chip. Therefore, trying to significantly increase the number of qubits (represented by the photons) proves to be a difficult task in the case of a photonic device, much more difficult than in the case of other systems, in which the qubits are located in space. Nevertheless, the evolution of this emerging technology promises efficient implementations in the near future [27].

Another technology that resembles the one of "trapping atomic ions" for obtaining qubits consists in the use and manipulation of neutral atoms by means of microwave radiation, lasers and optics. Just like in the case of the trapping atomic ions technology, the "cooling" process is achieved using laser sources. According to [1, 28], in 2018 there were implemented successfully quantum systems having 50 qubits that had a reduced space between them. By means of altering the space between the qubits, these quantum systems proved to be a successful analog implementation of quantum computers. In what concerns the error rates, according to [29], in 2018 there have been registered values as low as 3% within two-qubit quantum systems that managed to isolate properly the operations performed by nearby qubits. Since there are many similarities between the two technologies, the scaling up process faces a lot of the problems of the "trapping atomic ions" technology. However, the use of the neutral atoms technology offers the possibility of creating multidimensional arrays.

A classification of semiconductor qubits is made according to the method used to manipulate the qubits that can be achieved either by photon manipulation or by using electrical signals. Quantum dots are used in the case of semiconductor qubits that are gated by optical means in order to assure a strong coupling of the photons while in the case of semiconductor qubits manipulated via electrical signals, voltages are used upon lithographically metal gates for manipulating the qubits [1]. This quantum technology, although being less popular than other alternatives, resembles the existing classical electronic circuits, therefore one might argue that it has a better chance in attracting considerable investments that eventually will help speed up the scaling up process of quantum computers implementation.

In order to scale up qubits that are optically gated, one needs a high degree of consistency and has to process every qubit separately at the optical level. In [30], Pla et al. state that even if the qubits that are gated electrically can be very dense, the material related problems posed not long-ago serious quality problems up to single qubits gates level. Although the high density provided by this type of quantum technology creates opportunities for integrating a lot of qubits on a single processor, complex problems arise when one has to manipulate this kind of qubits because the wiring will have to assure an isolation of the control signals as to avoid interference and crosstalk.

Another ongoing approach in developing quantum computers consists in using topological qubits within which the operations to be performed upon are safeguarded due to a microscopically incorporated topological symmetry that allows the qubit to correct the errors that may arise during the computing process [1]. If in the future this approach materializes, the computational cost associated with correcting the quantum errors will diminish considerably or even be eliminated altogether. Although this type of technology is still in its early stages, if someday one is able to implement it and prove its technical feasibility, the topological quantum computers will become an important part of the quantum computing landscape.

## 4. CONCLUSIONS

Quantum computing represents a field in a continuous evolution and development, a huge challenge in front of researchers and developers, having the potential to influence and revolutionize the development of a wide range of domains like the computing theory, information technology, communications and, in a general framework, regarding from the time perspective, even the evolution and progress of society itself. Therefore, each step of the quantum computers' evolution has the potential to become of paramount importance for the humanity: from bits to qubits, from computing to quantum computing, an evolution on the verge of a revolution in the computing landscape.

## 5. REFERENCES

[1] National Academies of Sciences, Engineering, and Medicine, Quantum Computing: Progress and Prospects, Washington, DC: The National Academies Press, 2018, https://doi.org/10.17226/25196

[2] Osborne I. S., Counting the state of a qubit, Science, Vol. 361, Issue 6408, 2018, ISSN 0036-8075

[3] Waldrop M. M., The chips are down for Moore's law, Nature, Vol. 530, Issue 7589, 2016, ISSN 0028-0836

[4] Stanford Encyclopedia of Philosophy, The Church-Turing Thesis, https://plato.stanford.edu/entries/church-turing/ accessed on 22 March 2019

[5] Chen S., Atomic arrays power quantum computers, Science, Vol. 361, Issue 6409, 2018, ISSN 0036-8075

[6] Bernstein E., Vazirani U., Quantum Complexity Theory, Siam J. Comput, Vol. 26, Issue 5, 1997, ISSN: 0097-5397

[7] Shor P. W., Algorithms for quantum computation: discrete logarithms and factoring, in Proceedings of the 35th Annual Symposium on Foundations of Computer Science (SFCS '94), IEEE Computer Society, Washington, DC, USA, 1994, https://doi.org/10.1109/SFCS.1994.365700

[8] Shor P. W., Polynomial-Time Algorithms for Prime Factorization and Discrete Logarithms on a Quantum Computer, Siam J. Comput, Vol. 26, Issue 5, 1997, ISSN: 0097-5397

[9] Montanaro A., Quantum algorithms: an overview, npj Quantum Information, Nature Publishing Group, 2016, ISSN 2056-6387

[10] Garcia-Ripoll J.J., Zoller P., Circac, J. I., Fast and robust two-qubit gates for scalable ion trap quantum computing, Physical Review Letters, Vol. 91, Issue 15, 2003, ISSN 0031-9007

[11] Nakamura Y., Pashkin Y. A., Tsai J. S., Coherent control of macroscopic quantum states in a single-Cooper-pair box, Nature, Vol. 398, 1999, ISSN 0028-0836

[12] Nielsen M. A., Chuang I. L, Quantum Computation and Quantum Information, Cambridge University Press, 2010, ISBN 978-1-107-00217-3

[13] Stav T., Faerman A., Maguid E., Oren D., Kleiner V., Hasman E., Segev M., Quantum entanglement of the spin and orbital angular momentum of photons using metamaterials, Science, Vol. 361, Issue 6407, 2018, ISSN 0036-8075

[14] Höhn P.A., Quantum Theory from Rules on Information Acquisition, Entropy, Vol. 19, Issue 3, 2017, ISSN 1099-4300

[15] Chang L., Ge M., Frontier Problems in Quantum Mechanics, World Scientific Pub Co Inc, 2018, ISBN-10: 9813146842

[16] Rosario L. F., Compagno G., Quantum entanglement of identical particles by standard information-theoretic notions, Scientific reports, 2016, ISSN 2045-2322

[17] Rab A. S., Polino E., Man Z. X., Ba An N., Xia Y. J., Spagnolo N., Franco R. L., Sciarrino F., Entanglement of photons in their dual wave-particle nature, Nature communications, Vol. 8, Issue 1, 2017, ISSN 2041-1723.

[18] Akama S., Elements of Quantum Computing, Springer International Publishing, 2015, ISBN 978-3-319-08284-4

[19] Mcmahon D., Quantum Computing Explained, Wiley, 2016, ISBN-10: 8126564377

[20] Cirac J.I., Zoller P., Quantum Computations with Cold Trapped Ions, Physical Review Letters, Vol. 74, Issue 20, 1995, ISSN 0031-9007

[21] Monroe C., Meekhof D.M., King B.E., Itano W.M., Wineland D.J., Demonstration of a Fundamental Quantum Logic Gate, Physical Review Letters, Vol. 75, Issue 25, 1995, ISSN 0031-9007

[22] Brown K.R., Kim J., Monroe C., Co-designing a scalable quantum computer with trapped atomic ions, npj Quantum Information, Nature Publishing Group, 2016, ISSN 2056-6387

[23] Rudolph T., Why I am optimistic about the silicon-photonic route to quantum computing, APL Photonics, Vol. 2, Issue 3, 2017, https://doi.org/10.1063/1.4976737

[24] Linke N. M., Maslov D., Roetteler M., Debnath S., Figgatt C., Landsman K. A., Wright K., Monroe C., Experimental comparison of two quantum computers, Proceedings of the National Academy of Sciences, Vol. 114, No. 13, 2017, ISSN 1091-6490

[25] Oliver W. D., and Welander P. B., Materials in superconducting quantum bits, MRS bulletin, Vol. 38, Issue 10, 2013, ISSN 0883-7694

[26] Amato G., Greco A., Vittone E., Graphene Membrane as Suspended Mask for Lithography, Journal of Nanomaterials, Vol. 2018, Article ID 2396593, 2018, ISSN: 1687-4129

[27] Silverstone J.W., Bonneau D., O'Brien J.L., Thompson M.G., Silicon quantum photonics, IEEE Journal of Selected Topics in Quantum Electronics, Vol. 22, Issue 6, 2016, ISSN: 1558-4542

[28] Bernien H., Schwartz S., Keesling A., Levine H., Omran A., Pichler H., Choi S., Zibrov A.S., Endres M., Greiner M., Vuletić V., Lukin M.D., Probing many-body dynamics on a 51-atom quantum simulator, Nature, Vol. 551, 579-584, 2017, ISSN 0028-0836

[29] Levine H., Keesling A., Omran A., Bernien H., Schwartz S., Zibrov A.S., Endres M., Greiner M., Vuletić V., Lukin M.D., High-fidelity control and entanglement of Rydberg atom qubits, 2018, arXiv preprint arXiv:1806.04682

[30] Pla J.J., Tan K.Y., Dehollain J.P., Lim W.H., Morton J.J., Jamieson D.N., Dzurak A.S., Morello A., A single-atom electron spin qubit in silicon, Nature, Vol. 489, 541-545, 2012, ISSN 0028-0836