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State of the art of quantum computing its challenges and applications

Estado del arte de la computación cuántica sus desafíos y aplicaciones

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Abstract: The article is a review of the state of the art of quantum computing, its challenges, and applications. The project methodology is based on a rigorous and structured approach that begins with the identification of relevant databases and information sources in the field of quantum computing. Then, inclusion and exclusion criteria are defined to select pertinent studies. The selected studies undergo critical analysis, and relevant data is extracted. The challenges of quantum computing are identified and discussed in the context of current advances in the field. Potential and current applications of quantum computing are explored in detail. Finally, the findings are synthesized and presented in a coherent and understandable manner. This approach allows for a deep and up-to-date understanding of the state of the art of quantum computing, its challenges, and applications.

Keywords: quantum computing, systematic review, state of the art, challenges, applications.

Resumen: El artículo es una revisión del estado del arte de la computación cuántica, sus desafíos y aplicaciones. La metodología del proyecto se basa en un enfoque riguroso y estructurado que comienza con la identificación de las bases de datos y fuentes de información relevantes en el campo de la computación cuántica. Luego, se definen los criterios de inclusión y exclusión para seleccionar los estudios pertinentes. Los estudios seleccionados se someten a un análisis crítico y se extraen los datos relevantes. Los desafíos de la computación cuántica se identifican y se discuten en el contexto de los avances actuales en el campo. Las aplicaciones potenciales y actuales de la computación cuántica se exploran en detalle. Finalmente, los hallazgos se sintetizan y se presentan de manera coherente y comprensible. Este enfoque permite una comprensión profunda y actualizada del estado del arte de la computación cuántica, sus desafíos y aplicaciones.

Palabras clave: computación cuántica, revisión sistemática, estado del arte, desafíos, aplicaciones.

1. INTRODUCTION

In this paper, we will explore the basic concepts of quantum mechanics, the differences between quantum computing and classical computing, and the practical applications of quantum computing today. We will also discuss some of the most recent advances in quantum computing research, including the quantum supremacy achieved by IBM in 2021.

1.1. Classical Physics vs. Quantum Mechanics

Classical physics and quantum mechanics are two branches of physics that describe the behavior of matter and energy at different scales. Classical physics, known as Newtonian physics, was developed in the 17th century and describes the motion and interactions of macroscopic objects, such as planets, celestial bodies and everyday objects. On the other hand, quantum mechanics was developed in the 20th century and describes microscopic objects, studying the behavior of matter and energy at the atomic and subatomic level, such as atoms, molecules and subatomic particles, such as electrons and photons.

The origins of classical physics go back to antiquity. Already in Babylon, ancient Egypt and ancient Greece, where Greek philosophers, such as Aristotle, began to study the field of astronomy, optics and the motion of objects. In the 17th century when classical physics really began to develop, with the work of Galileo Galilei, Newton and other scientists.

Isaac Newton formulated the laws of motion in his work "Philosophiæ Naturalis Principia Mathematica" ("Mathematical Principles of Natural Philosophy"), published in 1687. These laws, also known as Newton's Laws, are the 3 fundamental principles on which classical mechanics, one of the branches of physics, is based, and his work in classical physics laid the foundations for modern science. [1]

Classical physics includes the study of Newtonian mechanics, thermodynamics, electromagnetism, optics among other disciplines. Classical physics has had a great impact on development, Newton's laws have been fundamental for the development of engineering, aviation and navigation. Einstein's theory of relativity has had an impact on the development of rocketry and space travel. Classical physics continues to evolve and is likely to continue to have a major impact on the development of technology in the future.

The origins of quantum mechanics date back to the 19th century, when scientists began to study phenomena that could not be explained by the laws of classical physics. In 1897, Joseph John Thomson discovered the electron, as a subatomic particle that has a negative charge. The discovery of the electron and other subatomic particles led to the realization that matter is made up of very small particles that obey laws different from those of macroscopic objects.

In the 20th century, quantum mechanics developed rapidly thanks to the work of scientists such as Mac Planck, Albert Einstein, Niels Bohr and Werner Heisenberg. Planck discovered that energy is emitted and absorbed in discrete packets called quanta. Einstein discovered that light is also a particle called a photon. Bohr developed an atomic model that explains the structure of the atom and the behavior of electrons. Heisenberg formulated the uncertainty principle, which states that it is impossible to know precisely the position and momentum of a subatomic particle at the same time. [2]

Quantum mechanics is a very complex and challenging branch of physics, but it has not helped to understand to understand the universe and has been instrumental in the development of new technologies, such as lasers, transistors and quantum computers and opens new possibilities for the development of new technologies.

***Table 1:** Comparison of Classical Physics vs. Quantum Mechanics*

Classical Physics	Quantum Mechanics
Deals with macroscopic objects, such as large objects and slow moving objects.	Deals with microscopic objects, such as atoms, molecules and subatomic particles.
It is based on Newton's laws, which describe the motion of objects.	It is based on the laws of quantum mechanics, which describe the behavior of matter and energy at the atomic and subatomic level.
It is a deterministic theory, which means that, if you know the initial state of a system, you can predict its future state.	It is a probabilistic theory, which means that it is not possible to predict with certainty the future state of a system, but only the probability that it will be in a certain state.

It is a very successful theory that has explained many phenomena in the everyday world.	It is a much more complex and difficult theory to understand than classical physics, but it has explained many phenomena that cannot be explained by classical physics, such as the behavior of light, the atom and nuclear energy.

2. METHODOLOGY

The project's methodology of systematically reviewing the state of the art of quantum computing, its challenges and applications, is based on a rigorous and structured approach. It starts with the identification of relevant databases and information sources in the field of quantum computing. Then, inclusion and exclusion criteria are defined to select relevant studies. The selected studies are subjected to a critical analysis and relevant data are extracted. The challenges of quantum computing are identified and discussed in the context of current advances in the field. Potential and current applications of quantum computing are explored in detail. Finally, the findings are synthesized and presented in a coherent and comprehensible manner. This approach provides a thorough and up-to-date understanding of the state of the art of quantum computing, its challenges and applications.

3. RESULTS

3.1. Brief History of Quantum Computing

The first quantum revolution took place between 1900 and 1930. During this time the principles of quantum mechanics, which is the theory that describes the behavior of matter and energy at atomic and subatomic scales, were developed.

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In the late 19th and early 20th century the prediction of the ultraviolet catastrophe was launched, also known as the Rayleigh-Jeans catastrophe which stated that an ideal black body in thermal equilibrium would emit an unlimited amount of energy as the wavelength decreased in the ultraviolet range. This law did not behave well at high frequency (short wavelengths) and predicted an infinite amount of energy emitted in the ultraviolet range, which contradicted experimental observations. This was resolved by the work of Max Planck.

Max Planck, a German physicist considered the father of quantum theory, solves the ultraviolet catastrophe in his article "Zur Theorie des Gesetzes der Energieverteilung im Normalspektrum" (On the theory of energy distribution in the normal spectrum), in the journal "Verhandlungen der Deutschen Physikalischen Gesellschaft" published in 1900. [1]

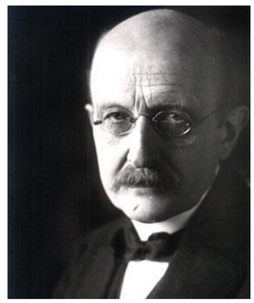

Fig. 1. *Max Plank. [3]*

In this article, Planck proposed that light energy is neither emitted nor absorbed continuously, but in small discrete quantities called quanta. This proposal, known as Planck's law, solved the ultraviolet catastrophe coined by Paul Ehrenfest in 1911. This work laid the foundation for the development of quantum theory and earned Plank the Nobel Prize in Physics in 1918. [2]

In 1913, Niels Borh was a Danish physicist who developed Bohr's model of atomic structure and introduced the theory of electrons orbiting the atomic nucleus. He was awarded the Nobel Prize in Physics in 1922 for his research on the structure of the atom and the radiation emanating from them. [4]

Fig. 2. *Neils Bohr. [5]*

Fig. 3. *Arnold Sommerfeld. [7]*

In 1916, Arnold Sommerfeld was a German physicist who perfected Bohr's atomic model by introducing two basic modifications; almost elliptical orbits for the electrons and relativistic velocities. [6]

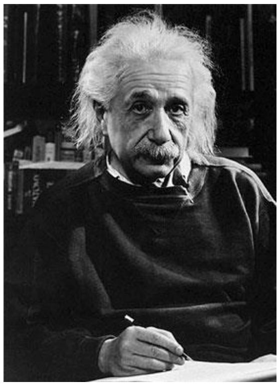

Fig. 4. Albert Einstein. [8]

Albert Einstein is considered one of the most important founders of quantum theory due to his description of light as quanta in his theory of the photoelectric effect, for which he received the Nobel Prize in 1921.

In 1922, Walther Gerlach was a German physicist who co-discovered spin quantization in a magnetic field, the now well-known Ster-Gerlach effect. The experiment was conceived by Otto Stern in 1921, and consisted of sending a beam of silver atoms through a homogeneous magnetic field. [9]

Spin was introduced by Ralph Kronig and, independently, first discovered in 1925 by Samuel Goudsmit and George Uhlenbeck. Goudsmit and Uhlenbeck were studying the emission line spectrum of the hydrogen atom. Spin is a physical property of elementary particles by which they have an intrinsic angular momentum of fixed value. [10]

Fig. 5. Werner Heisenberg. [12]

In 1927, Werner Heisenberg German theoretical physicist formulates the Heisenberg Uncertainty Principle, which states that it is impossible to accurately measure the position and linear momentum of a particle at the same time. [11]

In 1935, Albert Eistein, Boris Podolsky and Nathan Rosen published a paper that would become known as the EPR paradox. In this article the authors intended to demonstrate that Heisenberg's indeterminacy principle had exceptions in its application. [13], [14]

Paul Dirac published his paper entitled "A New Notation for Quantum Mechanics" in Volume 35, Number 3 of the Mathematical Proceedings of the Cambridge Philosophical Society in July 1939.

The new notation provides a concise and elegant way of writing both abstract quantities and their coordinates in a single scheme. This notation has been widely used in quantum mechanics and quantum computation. [15], [16]

Fig. 6. Paul Dirac. [17]

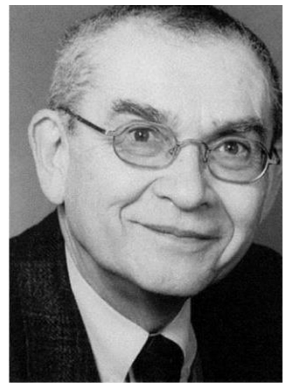

Fig. 7. Yuri Manin. [19]

In 1980, Yuri Manin, a Russian mathematician known for his work in quantum information theory, proposed in his book "Computable and Uncomputable" the idea of a quantum computer. [18]

In 1982, Paul Benioff is an American physicist whose article "Quantum Mechanical Models of Turing Machines That Dissipate No Energy" proposed an idea that the tape of the Turin machine could be replaced by a sequence of simple two-state quantum systems called qubits, providing a primitive way to encode a sequence of binary digits. [20]

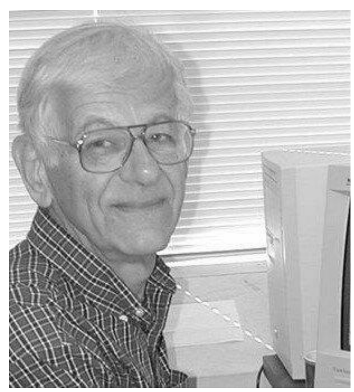

Fig. 8. Paul Benioff. [21]

In 1981, Richard Feynman, an American theoretical physicist, proposed the quantum computer model based on the combinational-logic circuit built with reversible quantum gates. In his paper "Simulating Physics with Computers" published in the International Journal of Theoretical Physics he proposed the idea of using quantum computers to

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simulate quantum systems that are difficult to simulate using classical digital computers. [22]

In 1985, David Deutsch is a British physicist who described the first universal quantum computer, capable of simulating any other quantum computer (Church-Turing principle). The Church-Turing thesis states "every algorithm is equivalent to a Turing machine", which hypothetically formulates the equivalence between the concepts of computable function and Turing machine. In 1989, he formulates the first quantum algorithm and is one of the formulators of the theory of parallel worlds. [24]

Fig. 8. *David Deutsch [25]*

In 1993, Charles H. Bennett, an American physicist working at IBM Research, proposed the quantum teleportation protocol, which makes it possible to transfer quantum information between two separate points and opened the way to the development of quantum communications.

In 1994, Dan Simon, an American computer scientist, invented the Simon algorithm, which provided the first example of exponential acceleration over the best quantum algorithm. He is currently a principal security engineer at AWS Cryptography. [26]

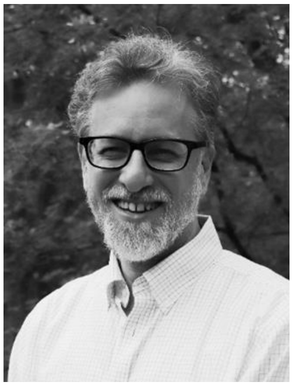

Fig. 9. *Dan Simon [27]*

In 1994, Peter Shor, an American mathematician at MIT, created Shor's quantum algorithm for factoring non-prime numbers in polynomial time. This algorithm when implemented on a practical quantum computer has the potential to make many public key cryptographies, such as RSA, obsolete. [28]

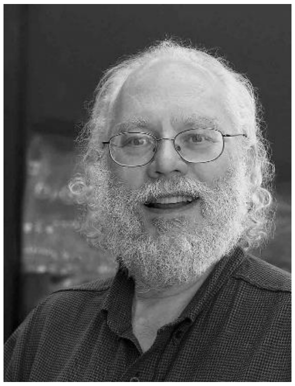

Fig. 10. *Peter Shor [27]*

In 1996, Lov Kumar Grover, an Indian-American computer scientist, invented Grover's quantum algorithm, an algorithm for unstructured search of an N-component sequence of data. The algorithm uses the properties of superposition and quantum interference to find with high probability the element satisfying a given condition, using only O(√N) and with additional need for storage space of O (log N) function evaluations. Grover's algorithm has applications function inversion, cryptography and optimization. [29]

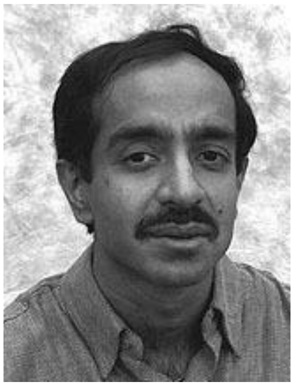

Fig. 11. *Lov Kumar Grover [30]*

In 1998, a team of researchers at Los Alamos National Laboratory and the Massachusetts Institute of Technology succeeded in propagating the first qubit through an amino acid solution. This was an important milestone in the development of quantum computing, since it made it possible to analyze the information carried by a qubit. [31]

The second quantum revolution is currently taking place. During this time, new technologies are being developed that are based on the principles of quantum mechanics.

That same year, the University of Berkeley, California, presented the first 2-qubit machine. A year later, in 1999, IBM-Almaden Laboratories created the first 3-qubit machine, which was able to run Grover's search algorithm for the first time.

D-Wave Systems is founded in 1999 by Haig Farris, Geordie Rose, Bob Wiens and Alexandre Zagoskin a private quantum computing company based in

Burnaby. D-Wave Systems is the first private company to sell quantum computers, launching its first commercial system in 2010, the D-Wave ONE. Since then, the company has released several models such as the D-Wave two, a 512-qubit system. In August 2015, they launched the D-Wave 2X, a 1000-qubit system. [32]

In 2005, a team of researchers at the Institute for Optics and Information at the University of Innsbruck in Austria announced that they had created the first Qbyte, a series of qubits using ion trapping. The experiment used a cesium atom cooled near absolute zero and confined in a magnetic trap. The researchers then used a laser to manipulate the spin of the atom, which is a form of quantum information.

In 2006, several important advances in quantum control were made. C, Negrevergne and other researchers presented an experimental benchmark of operational control methods on quantum information processors extended up to 12 qubit. They implemented universal control of this large Hilbert space using two complementary approaches and discussed their accuracy and scalability. In the same year, Fei Xue and other researchers conducted a quantum controllability study under the influences of induced quantum decoherence on quantum control itself.

In 2016, IBM was the first company to connect a small quantum computer in its IBM Cloud. Since then anyone can access a selection of quantum cloud services based on IBM Quantum System One technology to perform research and explore new problems in their systems. [33]

D-Wave Systems launched the D-Wave 2000Q in January 2017, it is an enhancement of the D-Wave 2X that features a 2000 qubit system and some advanced features.

In January 2019, IBM introduced the first commercial IBM Q System One quantum computer based on 20-qubit circuits from IBM Research, it uses a dilution cooling system to cool the qubits to a temperature near 0.02K. The qubits are made of silicon nitride and 5cm diameter chips. [34]

In 2019, Google announced that it had achieved "Quantum Supremacy" by employing its 53-qubit Sycamore quantum processor by completing a 200-second task that would have taken a faster supercomputer in the world 10,000 years. [35]

The latest model is D-Wave's Advantage system launched on September 29, 2020 is the first quantum computer designed specifically for commercial applications and can handle larger and more complex problems thanks to an increase by 500 in the number of qubits and 35,000 in the number of couplers. [36]

Fig. 12. *D-WAVE Advantage [37]*

On November 23, 2021, IBM announced that it had achieved quantum supremacy with its "Eagle" quantum computer with a processor that can handle 127 qubits. [38]

3.2. Basic Concepts of Quantum Mechanics

3.2.1. Heisenberg's Uncertainty Principle

W. Heisenberg formulated in 1927 the Heisenberg uncertainty principle which is a fundamental constraint is the ability to know precisely certain pairs of characteristics of a measured physical object, such as the position and momentum (or velocity) of a subatomic particle at the same time. This is because the observation of the particle alters its state and behavior. [39]

3.2.2. Superposition state

In 1924, the French Duke Louis de Broglie introduced the idea of the wave nature of electrons and the particle-wave duality. His research laid one of the cornerstones of quantum physics: wave-particle duality states that waves can behave like particles and vice versa. De Broglie calculated what would be the length of the matter waves associated with the particle, depending on its velocity and mass. According to Broglie, our whole world is quantum, not just light.

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The thought experiment proposed in 1935 by the Austrian scientist Erwin Schrödinger, known as "Schrödinger's cat", is a paradox that shows how puzzling quantum mechanics is. The experiment consists of a cat in a sealed box with a radioactive atom, a Geiger detector, a vial of poison and a hammer. If the atom disintegrates, the Geiger detector will detect it and activate the hammer, which will break the poison vial and kill the cat. In the paradox posed by Schrödinger, who received the Nobel Prize in Physics in 1933, the cat is alive and dead at the same time. [40]

Fig. 13. *Gato de Schrödinger [40]*

In quantum mechanics, the superposition state is a fundamental principle that holds that a physical system such as an electron can be in two or more states at the same time. This means that the system does not have a single definite position, velocity or spin, but is in a combination of all possible states. Superposition is responsible for many quantum phenomena such as interference and teleportation. [41]

3.2.3. *Quantum entanglement*

Jhon Stewart Bell was an Irish theoretical physicist and mathematician Bell's theorem. In 1064, Bell published "On the Einstein-Podoslky-Rosen paradox" in which he presented Bell's inequality, which is a constraint on the correlation between the results of measurements performed on entangled particles. Bell's inequality has been confirmed in numerous experiments, which has led to the widespread acceptance of quantum entanglement as a fundamental property of nature. The phenomenon that bears its name is used in practical applications such as quantum computing and cryptography. [42]

Quantum entanglement is a quantum phenomenon in which the quantum states of two or more objects need to be described by a single state. Entangled particles are connected in such a way that they share the same quantum state, even if they are separated by a great distance, even if they are separated by millions of light years. Entanglement is a phenomenon with no classical equivalent. Their shared state can be their energy or their spin. It is a strange phenomenon that Albert Einstein called "ghostly action at a distance". [43]

The 2022 Nobel Prize in Physics went to Frenchman Alain Aspect, American John Clauser and Austrian Anton Zeilinger their work could pave the way for a new generation of powerful computers and unhackable telecommunication systems. [44]

3.2.4. *Decoherence state*

Quantum decoherence is a process by which the loss of coherence of a quantum state occurs. It can be understood as the destruction of quantum interference; interference is the result of one of the most peculiar features of quantum mechanics, the principle of superposition of states, which means that it can be in two states at the same time.

Quantum decoherence is caused by the interaction of a quantum system with its environment (e.g., such as light, heat or vibrations). Quantum decoherence is an inevitable process when a quantum system interacts with its environment, quantum coherence is lost, this is because the environment introduces noise into the quantum system, which causes it to go from being in superposition of states to a single state. Quantum decoherence can be slow or fast depending on the environment. It also makes quantum systems more error prone. [45]

3.2.5. Bit vs Qubit

A bit is the basic unit of information in classical computers; it can take two values, 0 or 1. A qubit or quantum bit, on the other hand, is the basic unit of information in quantum computing. Unlike a classical bit, which can only take the values 0 or 1, a qubit can be in a quantum superposition state, a combination of these two states. This means that a qubit can contain both values (0 and 1) at the same time. For example, a qubit in superposition has a 50% probability of being measured as 0 and a 50% probability of being measured as 1. However, once a qubit is measured, its quantum state collapses into one of its two eigenstates (0 or 1).

Qubits can be constructed in a variety of ways, but all represent a digital 0 or 1 using the quantum properties of something that can be controlled electronically. Some well-known examples are superconducting circuits, in which qubits are created by manipulating the state of a tiny electric current, and trapped ions, in which qubits are created by manipulating the state of individual ions using lasers. There are also topological qubits, which are created by manipulating the properties of materials that exhibit topological phases, and photonic qubits, in which quantum information is stored in the polarization of individual photons.

The differences between bits and qubits have a number of important effects. Qubits can perform calculations that would be impossible for bits, and can do so much faster. This makes quantum computers much more powerful than classical computers.

3.2.6. Dirac Notation

The notation for representing quantum bits is called Dirac notation. Also known as bra-ket notation, it is a way of representing quantum states and operators in quantum mechanics and was developed by the physicist Paul Dirac. The first article in which these notations appear is "A new notation for quantum mechanics", published in 1939 in the journal "Mathematical Proceedings of the Cambridge Philosophical Society". [46]

3.2.7. Mathematical representation of Qubits

The fundamental element of all computers is a memory cell called a bit (a contraction of binary digit), which can exist in two states. Quantum computing and information is based on an analogous concept, the quantum bit or qubit.

3.2.8. Dirac Bra-Ket Notation

The two possible states of a qubit are$|0\rangle$ and$|1\rangle$, which correspond to the 0 and 1 states of a classical bit. The notation is called Dirac notation. The difference between bits and qubits is that a qubit can be in a state other than$|0\rangle$ and$|1\rangle$. It is also possible to form linear combinations of state, often called superpositions.

$$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle. (1)$$

The numbersα andβ called amplitudes are complex numbers. The amplitudes are very important because they give us the probability of finding the particle in that particular state when making the measurement. The probability of measuring the particle in the state$|0\rangle$ is$|\alpha|2$ and the probability in the state$|1\rangle$ is$|\beta|2$. Squaringα andβ to find the probability is similar to squaring the wave amplitude to find the wave energy. Since the total probability of observing all states of the quantum system must add up to 100%. The amplitudes must obey this rule:

$$|\alpha|^2 + |\beta|^2 = 1. (2)$$

This is called the normalization rule. The coefficientsα andβ can always be rescaled by some factor to normalize the quantum state.
In other words, the state of a qubit is a vector in a two-dimensional complex vector space. The states$|0\rangle$ and the$|1\rangle$ are known as computational basis states and form the orthogonal basis for this vector space. When a qubit is measured, the result of the measurement can only be "0" or "1", probabilistically. For example, a qubit can be in the state.

$$\frac{1}{\sqrt{2}}|0\rangle + \frac{1}{\sqrt{2}}|1\rangle. (3)$$

Which when measured, gives the result 0 50% $\left(|1/\sqrt{2}|^2\right)$ of the time and the result 1 50% of the time. We will often return to this state, which is sometimes denoted as .$|+\rangle$.

3.3. Matrix Representation

When writing a single qubit in a superposition$|\varphi\rangle = \alpha|0\rangle + \beta|1\rangle$, it is useful to use matrix algebra. In matrix representation, a qubit is written as a two-dimensional vector where the amplitudes are the components of the vector. [47]

$$|\psi\rangle = \binom{\alpha}{\beta}. \qquad (4)$$

The states$|0\rangle$ and$|1\rangle$ are typically represented as

$$|0\rangle=(1¦0),\ |1\rangle=(0¦1). (5)$$

Experimentally, the state of a qubit can be changed by some physical action, such as applying an electromagnetic laser or, passing it through an optical device. Changing the state of a qubit by a physical action corresponds mathematically to multiplying the qubit sector$|\psi\rangle$ by some unitary matrix U, so that after the operation the state is now. $|\psi'\rangle = U|\psi\rangle$.

3.4. Bibliometric Visualization of Emerging Trends in Quantum Computing

For this study it is fundamental to generate bibliometric maps, which facilitate the visualization of relationships and similarities between keywords,

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grouping terms into thematic clusters, highlighting areas of concentration and emerging trends in quantum computing. VOSviewer is an application that allows to analyze and explore graphically large volumes of data, facilitating the detection of patterns, allowing a more intuitive and didactic interpretation of the results.

The documents retrieved in SCOPUS were 6,298 in a time window from 1996 to 2025, which were analyzed in relation to the subject of "Quantum Computing", managing to extract the most relevant keywords related to the subject, Table 2 presents a list of the 20 most relevant keywords in terms of occurrence of occurrence and link strength in the analyzed documents.

***Table 2:** List of keywords by importance of occurrence and link strength.*

KEYWORD (KEYWORD)	OCCURRENCES (OCURRENCES)	TOTAL LINK STRENGTH (TOTAL LINK)
QUANTUM COMPUTING	4806	32473
QUANTUM COMPUTERS	4490	32049
QUANTUM OPTICS	1972	16781
QUANTUM THEORY	1089	8000
QUANTUM ELECTRONICS	893	7767
QUBITS	801	6408
COMPUTATION THEORY	721	6182
QUANTUM CRYPTOGRAPHY	709	5751
QUANTUM ALGORITHMS	620	5302
QUANTUM ENTANGLEMENT	592	5219
QUANTUM CIRCUIT	564	5439
TIMING CIRCUITS	473	4652
LOGIC GATES	460	4579
QUANTA COMPUTERS	417	3698
QUANTUM COMMUNICATION	369	3156
MACHINE-LEARNING	366	3845
MACHINE LEARNING	344	3268
PHOTONS	341	2925
OPTIMIZATION	327	2667
COMPUTER CIRCUITS	322	3211
QUANTUM MACHINES	292	3148

The bibliometric map that represents the different topics grouped in clusters by areas with predominant approaches in the literature, allows to visualize the key concepts within the research field "Quantum Computing" facilitating its understanding and its internal structure.
Each cluster represents a set of words related to each other reflecting lines of research.

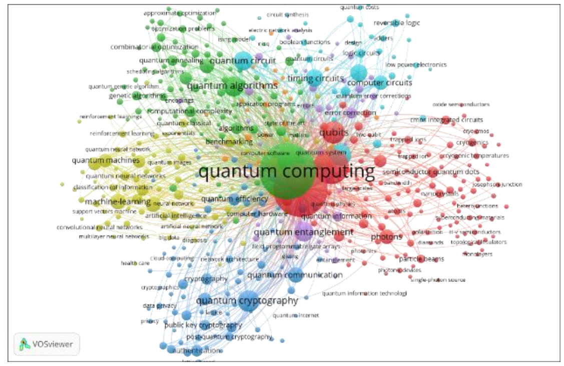

***Fig. 14.** Clusters network of keywords in scientific publications on Quantum Computing*
***Source**: Prepared by the authors based on the VOSviewer 1.6.20 program*

- Cluster 1 (red): Includes terms such as Quantum computer, Quantum applications, Quantum technologies, qubit, the cluster groups 125 elements.
- Cluster 2 (green): Includes terms such as Quantum algorithms, approximate optimization, computer science, the cluster groups 94 elements.
- Cluster 3 (blue): Includes terms such as computer architecture, cloud computing, post quantum, quantum network, the cluster groups 93 elements.
- Cluster 4 (yellow): Includes terms such as artificial intelligence, big data, clustering algorithms, Deep learning, the cluster groups 74 elements.
- Cluster 5 (purple): Includes terms such as errors, encoding, code, fault tolerance, the cluster includes 43 elements.
- Cluster 6 (light blue): Includes terms such as circuit optimization, computer circuits, cost, logic design, the cluster groups 41 elements.
- Cluster 7 (orange): Includes terms such as computer software, program compilers, software design, the cluster groups 26 elements.

Figure 15 corresponds to the keyword network, with a timeline approach that allows understanding the evolution of research in the field of quantum computing between 1996 and 2025. The figure shows how some keywords such as "quantum machines" and "quantum neural networks" have been recurrent in the current literature, evidencing the topics that have received the most attention in the analyzed period.

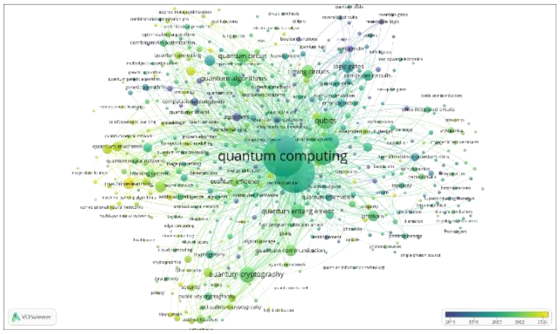

Fig. 15. *Temporal evolution of the keyword network in scientific publications on Quantum Computing.*
Source: *Prepared by the authors based on the VOSviewer 1.6.20 program.*

Figure 16 presents a map of keyword density in scientific publications on "Quantum Computing", generated using the VOSviewer software based on data from the Scopus database in 2025. This figure provides a quantitative and qualitative view on the intensity and relevance of different terms in the literature of the field, facilitating the identification of priority areas and challenges in research.

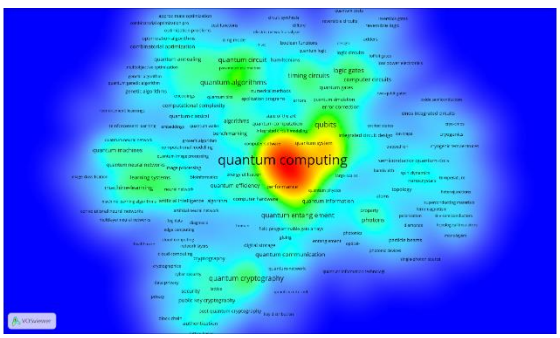

Fig. 16. *Keyword density in scientific publications on Quantum Computing.*
Source: *Prepared by the authors based on the VOSviewer 1.6.20 program*

4. CONCLUSIONS

In conclusion, quantum computing is an emerging technology that has the potential to revolutionize the way we process and store information. Unlike classical computing, which uses bits to represent information, quantum computing uses qubits, which can be in multiple states at the same time. This allows quantum computers to perform much faster and more complex calculations than classical computers.

Although quantum computing is still in its early stages of development, practical applications are

already being explored in areas such as cryptography, simulation of complex systems and optimization of business processes. Moreover, recent advances in quantum computing research, such as the quantum supremacy achieved by IBM in 2021, suggest that this technology has a bright future.

In summary, quantum computing is an exciting and promising technology that has the potential to transform the way we live and work. As research continues to advance, we are likely to see more and more practical applications of quantum computing in the near future.

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