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ARCHITECTURE OF QUANTUM COMPUTING

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Abstract: Quantum computing is emerging as a revolutionary paradigm in the field of computing, promising an exponential leap in computing power and problem-solving that challenges even the most advanced supercomputers of the classical era. At the heart of this revolution lies the peculiarity of the quantum world, where subatomic particles can exist in multiple states simultaneously, a phenomenon known as superposition, and entangle their states in a way that defies classical logic. It is this capacity for superposition and entanglement that gives quantum computing its disruptive power. One of the most intriguing properties of quantum computing is its ability to process information using Qubits, the quantum analogues of classical bits. While a classical bit can only be in a single 0 or 1 state, a Qubit can simultaneously represent a 0, a 1, or any superposition of these states, allowing multiple calculations to be performed in parallel. This massively parallel processing capability is the basis for the potential superiority of quantum computers over their classical counterparts in a wide range of applications. The architecture of quantum computers is inherently different from classical computers. While the latter use transistors to store and manipulate information in bits, quantum computers use Qubits, which can be implemented in a variety of physical systems, such as atoms, ion traps, photons, superconductors or nuclear magnetic resonance. The manipulation of the Qubits is carried out through quantum gates, fundamental operations that transform the quantum state of the Qubits and allow quantum calculations to be carried out. Furthermore, to maintain quantum coherence, the control and isolation of the quantum system from its environment is crucial, posing significant challenges in terms of designing and building scalable and robust quantum systems.

Keywords: Quantum Computing, Quantum Computer, Qubit (quantum bit), Quantum Logic Gate, Quantum Circuit.

INTRODUCTION

The evolution of computers has been a fascinating journey that has transformed the way we live, work and communicate in modern society. From the first rudiments of calculus to the wonders of quantum computing, each stage has been driven by advances in technology and the understanding of science. From the early days of the abacus to the rise of quantum computing, computers have been built from a variety of materials that reflect both the availability of resources and advances in engineering.

The emergence of the Internet in the 1990s completely transformed the way computers were used and connected to each other. Modern computers are built from a variety of materials, from metals like aluminum and steel for the case to silicon for the processor and memory chips. Advances in nanotechnology have allowed the manufacturing of even smaller and more efficient components, driving the development of portable and wearable devices.

The future of computing appears to lie in quantum computing, a technology that leverages the principles of quantum mechanics to perform calculations at astonishing speeds. Unlike classical computers, which use bits to represent information, quantum computers use Qubits, which can be in multiple states simultaneously thanks to a phenomenon called superposition.

These machines are built with materials such as superconductors and specific semiconductor materials that can operate at extremely low temperatures to maintain the stability of the Qubits.

In summary, the evolution of computers from the early days with the abacus to the era of quantum computing has been driven by advances in technology and scientific understanding. Over the centuries, computers have been built from a variety of materials, from wood and metal to silicon and quantum materials, reflecting both the availability of resources and advances in engineering and science.

The miniaturization of classical computing has played a crucial role in bringing us closer to quantum computing based on the laws of quantum mechanics. As technological advances have enabled the manufacturing of smaller, more efficient components, we have been able to explore and better understand the fundamental principles of quantum physics. The ability to design and manufacture increasingly tiny devices has laid the foundation for the creation of the circuits and systems necessary for quantum computing, which depends on the precise manipulation and control of the quantum states of Qubits. The experience accumulated in the miniaturization and optimization of classical computing has paved the way for the construction of the complex architectures necessary for quantum computing, representing an exciting bridge between two seemingly disparate worlds, but intrinsically interconnected in technological progress.

The development of a quantum computer presents a number of significant technical and scientific challenges. One of the main problems lies in the need to maintain the quantum coherence of the Qubits for long periods, since any external interference can alter their state. Furthermore, building reliable and scalable Qubits is complicated due to the extreme sensitivity of quantum systems to environmental fluctuations. Another major challenge is quantum error correction, as Qubits are inherently error-prone due to the fragility of quantum states. These challenges require significant advances in materials engineering, cryogenic cooling, and the development of robust quantum algorithms. To illustrate the power difference between classical and quantum computing, let's consider a complex optimization problem, such as finding the optimal solution in a large data set. While a classical computer would approach this problem by sequentially evaluating each possible solution, a quantum computer could simultaneously explore multiple solutions thanks to the superposition of quantum states. Furthermore, using the property of quantum entanglement, a quantum computer could perform parallel operations on all possible solutions, potentially leading to a much faster and more efficient search for the optimal solution. This example illustrates how quantum computing has the potential to significantly surpass the limits of classical computing on certain types of complex problems.

The organization of this article is such that in the second section the foundations and basic elements that make up quantum computing are developed; Mathematical expressions have been used to show the representation of the states of a quantum bit and the mechanism of quantum parallelism. The third section presents one of the most widely accepted quantum architecture proposals in the scientific community. This proposal consists of elements similar to current architectures to ensure compatibility; but at the same time with the elements of quantum computing. The fourth section lists the conditions known as Di Vincenzo's list that the physical support must meet to carry out quantum computing tasks.

QUANTUM COMPUTING

Exploration in the field of quantum computing has revealed monumental theoretical achievements, evidencing the possibility of drastically reducing the computational resources necessary for the execution of algorithms. Some of these algorithms demand colossal computing power, even for today's most advanced computers. Among the most notable advances are mathematical algorithms such as the factorization of prime numbers and search algorithms in disordered databases, which have been developed with great success in the theoretical field, thanks to the foundations of quantum computing.

The theory of quantum computing is based on the interactions of the atomic world and the future implementations of quantum computers. Although these implementations are still confined to research laboratories, the results obtained so far are encouraging. A notable example is the development of the five-Qubit quantum computer, carried out by Steffen, which represents a significant milestone on the path towards the practical realization of quantum computing. (Steffen, 2001)

FUNDAMENTALS OF QUANTUM COMPUTING

Quantum computing is based on the principles of quantum mechanics, a theory that describes the behavior of subatomic particles. Unlike classical bits, which can represent a state as 0 or 1, quantum qubits can be in a superposition of both states simultaneously. Additionally, Qubits can become entangled, meaning that the state of one Qubit can depend on the state of another, even if they are separated by enormous distances. These properties allow quantum computing to perform certain tasks exponentially more efficiently than classical computers.

However, building and maintaining stable Qubits and correcting errors are significant technical challenges that must be overcome to achieve the practical realization of large-scale quantum computing.(Caituiro-Honge, S/F)

BASIC ELEMENTS OF QUANTUM COMPUTING

QUBIT

A Qubit or quantum bit (Qubit) is the basic unit of information in quantum computing. Unlike classical bits, which can represent a state as 0 or 1, a Qubit can be in a superposition of both states simultaneously, thanks to the principles of quantum mechanics. This superposition is represented by a vector in two-dimensional complex space, where the direction and length of the vector indicate the probability that the Qubit is in a particular state. Figure 1 is a Bloch sphere graphically representing a Qubit, where each point on the sphere corresponds to a unique state of the Qubit. For example, the ground state $|0\rangle$ is represented at the north pole of the sphere, while the state $|1\rangle$ is represented at the south pole according to Dirac notation. The states in superposition found at other points on the sphere of type $|\psi\rangle$ are called kets. This visual representation makes it easier to understand and manipulate quantum states in quantum computing. (Vidick, T., & Wehner, S. 2023)

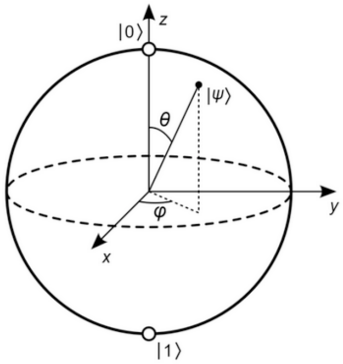


Figure 1: Graphic representation of a Qubit using the Bloch sphere.

Another way to represent the basic states of one or more Qubits is through vectors. Later we will see that this representation makes it easier to visualize, for example, how quantum logic gates act in one or more Qubits.

$$\text{Qubit in state } 0 \text{ is represented by the ket} |\mathbf{0}\rangle = \begin{pmatrix}\mathbf{1}\\ \mathbf{0}\end{pmatrix}$$

$$\text{Qubit in state } 1 \text{ is represented by the ket} |\mathbf{1}\rangle = \begin{pmatrix}\mathbf{0}\\ \mathbf{1}\end{pmatrix}$$

A vector of two Qubits can simultaneously represent all states:

$$|\mathbf{00}\rangle = \begin{pmatrix}\mathbf{1}\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\end{pmatrix}, \quad |\mathbf{01}\rangle = \begin{pmatrix}\mathbf{0}\\ \mathbf{1}\\ \mathbf{0}\\ \mathbf{0}\end{pmatrix}, \quad |\mathbf{10}\rangle = \begin{pmatrix}\mathbf{0}\\ \mathbf{0}\\ \mathbf{1}\\ \mathbf{0}\end{pmatrix}, \quad |\mathbf{11}\rangle = \begin{pmatrix}\mathbf{0}\\ \mathbf{0}\\ \mathbf{0}\\ \mathbf{1}\end{pmatrix}$$

With this we notice that a vector of Qubits can represent 2^n states.

QUANTUM LOGIC GATES

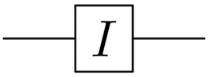
A quantum logic gate is a basic circuit that operates on a small number of Qubits, these are equivalent to the logic gates used in classical computing. A unique characteristic is that all quantum logic gates are reversible and, like Qubits, it is possible to represent them using matrices.

The most commonly used logic gates act on one or two Qubits. This means that they can be represented as 2x2 or 4x4 dimensional matrices respectively with orthonormal rows. Below are the most used ones in the literature.

Identity Gate

This gate is the identity matrix, usually identified as I.

$$\boldsymbol{I} = \begin{bmatrix}\mathbf{1} & \mathbf{0}\\ \mathbf{0} & \mathbf{1}\end{bmatrix}$$

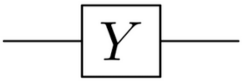


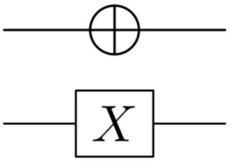
Pauli gates (X, Y, Z)

The gates are the three matrices (σx, σy, σz). They operate with a single Qubit, these gates rotate around the **x, y, and z** axes in the Bloch sphere in **π** radians. As an observation, the Pauli X gate is the quantum equivalent of the NOT (negation) logic gate of classical computing. These matrices are represented as:

$$\boldsymbol{Y} = \sigma y = \begin{bmatrix}\mathbf{0} & -\boldsymbol{i}\\ \boldsymbol{i} & \mathbf{0}\end{bmatrix}$$

$$\boldsymbol{X} = \sigma x = \boldsymbol{NOT} = \begin{bmatrix}\mathbf{0} & \mathbf{1}\\ \mathbf{1} & \mathbf{0}\end{bmatrix}$$





$$\boldsymbol{Z} = \sigma z = \begin{bmatrix}\mathbf{1} & \mathbf{0}\\ \mathbf{0} & -\mathbf{1}\end{bmatrix}$$

Hadamard gate

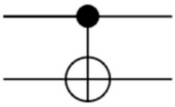
This gate operates with a single Qubit, it performs a rotation of π around the axis on the Bloch sphere; The Hadamard gate is the representation of a Qubit of the quantum Fourier transform, matrix-wise it is represented as follows:

$$\boldsymbol{H} = \frac{\mathbf{1}}{\sqrt{\mathbf{2}}}\begin{bmatrix}\mathbf{1} & \mathbf{1}\\ \mathbf{1} & -\mathbf{1}\end{bmatrix}$$

Controlled NOT or CNOT doors

Controlled gates operate on two or more Qubits, of which one or more controls the operation. An example would be the controlled NOT gate (or CNOT) that operates on two Qubits, and performs the NOT operation on the second Qubit only when the first is $|1\rangle$, otherwise it leaves its state intact. It is represented as follows:

$$CNOT = \begin{bmatrix}1 & 0 & 0 & 0\\ 0 & 1 & 0 & 0\\ 0 & 0 & 0 & 1\\ 0 & 0 & 1 & 0\end{bmatrix}$$



PROPERTIES OF A QUBIT; OVERLAPPING AND INTERLACING

Superposition in a quantum qubit is a fundamental concept in quantum computing. A quantum qubit, unlike a classical bit which can only be in a state of 0 or 1 at any given time, can exist in a superposition of both states simultaneously.

Imagine that a quantum Qubit is like a sphere, where the north pole represents state 0 and the south pole represents state 1. In the superposition, the Qubit is neither at the north pole nor at the south pole, but somewhere on the sphere, which means it is in a linear combination of both states.

This superposition is what allows quantum algorithms to perform certain tasks more efficiently than classical algorithms. For example, in a quantum search algorithm, multiple possibilities can be evaluated simultaneously thanks to superposition, leading to an exponentially faster search speed compared to classical algorithms.

In general the superposition of a Qubit can be represented in the following way:

$$|\psi\rangle = \alpha|0\rangle + \beta|1\rangle$$

Quantum entanglement is another extraordinary phenomenon in quantum physics that occurs when two quantum qubits are correlated in a way that is beyond what can be explained by the laws of classical physics. In other words, the state of one Qubit is intrinsically related to the state of the other, regardless of the distance between them.

When two Qubits are entangled, the state of one cannot be described independently of the state of the other, even if they are separated by astronomical distances. This means that if the state of one of the Qubits is measured, the state of the other is instantly known, no matter how far away they are.

This phenomenon has led to numerous applications in quantum computing and cryptography, as quantum entanglement provides a way to securely communicate and perform operations that exceed the limits of classical systems. Furthermore, quantum entanglement is fundamental to understanding the nature of quantum mechanics and has been the subject of intense research in theoretical and experimental physics.(García P.J., & Bastarrachea M.A. 2022)

QUANTUM ERROR CORRECTION

The non-localized properties of quantum states mean that localized errors in a few Qubits can have a global impact on the exponentially large state space of many Qubits. Therefore, quantum error correction is perhaps the most important concept when designing a quantum architecture. Unlike classical systems, which can perform brute force error correction and signal-level restoration on each transistor, quantum state error correction requires a subtle and complex strategy.

QUANTUM COMPUTER ARCHITECTURE

Based on the theory of quantum computing, the basic components of a general architecture can be defined that allow minimizing the overhead when correcting errors. In contrast to other models found within the quantum literature, this architecture allows the support of different algorithms, as well as different sizes of information. The key mechanisms in this proposal are reliable channels through which information travels, as well as an efficient quantum memory structure. Quantum computing is similar in several ways to classical computing. For example, the control flow of a quantum algorithm is well defined and allows the manipulation of elements and information during its execution. On the other hand, the physical constraints of quantum technology also resemble classical technology.

And although two Qubits can interact over long distances thanks to their properties, the strongest interaction occurs between close neighbors, but to achieve this classical support circuits are needed throughout the system.

It is worth mentioning that this quantum computer proposal has similarities to a classical one; some calculation mechanisms are exclusive to the quantum field. Figure 2 shows the three main components of this architecture: The quantum logic arithmetic unit (UAL), quantum memory, and a dynamic scheduler. Furthermore, this proposal implements a quantum wiring technique that exploits quantum teleportation. (Lidar, D. A., Chuang, I. 1998)

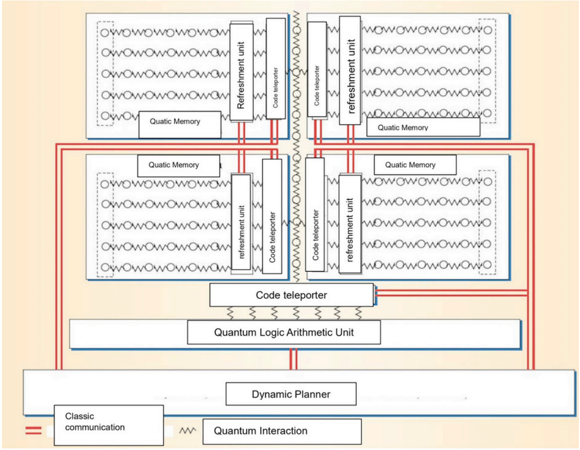


Figure 2. Proposed quantum computer architecture.

QUANTUM LOGIC ARITHMETIC UNIT

The central part of this architecture is the Quantum Arithmetic Logic Unit (ALU). This component is the one that performs quantum operations for both calculation and error correction. To efficiently execute any specified quantum gate on quantum data, quantum UAL applies a sequence of basic classically controlled quantum transformations, these transformations are:

- Hadamard (square root, Fourier transform on a Qubit)
- Identity (I, NOP Quantum)
- Bit change (X, NOT quantum)
- Phase change (Z, changes the signs of the amplitudes)
- Bit and phase change (AND)
- Rotation by π/4 (S),
- Rotation by π/8 (T), and
- Not controlled (CNOT).

These gates form one of the smallest possible universal sets for quantum computing. Quantum physics technology can efficiently implement these gates on encoded data. They all work with a single Qubit, except for CNOT which works with two. To perform error correction tasks, the quantum arithmetic logic unit (ALU) applies a sequence of operations.

Since this task is necessary for fault-tolerant quantum computing, the ALU performs it on the encoded data after most logical operations. This procedure consumes wizard states, which help in the calculation of parity checks. Specialized hardware provides elementary standard states that the ALU uses to fabricate the necessary assistant states. (Figueroa-Nazuno J, 2008)

QUANTUM MEMORY

The generality of the architecture depends on efficient quantum memory. The key is to build quantum memory banks that are more reliable than quantum computing devices. We can also use specialized "refreshment" units much less complex than a classic ALU.

The storage of Qubits not subjected to computation is very similar to that of conventional dynamic RAM. Just as the individual capacitors used for DRAM leak into the surrounding substrate over time, Qubits couple to the surrounding environment and undergo decohesion over time. This requires periodically refreshing the individual Logical Qubits. As Figure 2 shows, each Qubit memory bank has a dedicated refresh unit that periodically performs error detection and recovery on the logical Qubits. From a technological point of view, decoherence-free subsystems, which naturally provide lower decoherence rates for static Qubits, could implement these quantum memories.

The architecture allows the use of multiple quantum memory banks, but they are not with the objective of improving logical access times to the Qubits. In fact, factors such as the error rate of the physical storage mechanism of the qubits, the complexity of the algorithm, the size of the input data, the execution time and the parallelism of the quantum arithmetic logic unit (ALU), as well as The error-correcting code that stores the logical qubits are factors that limit the number and size of memory banks. For example, if you work with Shor's algorithm on a 1024-bit number using a memory technology with an error rate of $p = 10^{-9}$, you estimate using 28,000 physical qubits to represent about 1,000 physical bits using two levels of recursion in a 5-qubit error-correcting code. On the other hand, if the error rate increases to $p = 10^{-6}$, error correction would require four levels of recursion to refresh a memory bank of only 1,000 physical qubits that would store only two logical qubits.

QUANTUM CABLES

The movement of information through a quantum computer is challenging, quantum operations must be reversible, and it is not possible to clone Qubits identically; that is we cannot copy their values. It is not possible to connect a Qubit to a cable and be able to transmit its current state. To resolve this situation, the proposal is to rely on a basic quantum concept, quantum teleportation.

Quantum teleportation is a process in which quantum information is transmitted from one position to another sufficiently far away (assuming an entangled state between both locations) through a classical channel. Due to this detail, information will not be able to travel faster than the speed of light, however, it is superior to other means of transport in a quantum state. Physical qubits cannot move, but we can apply a swap operation to progressive pairs of atoms to send the values of the qubits through a stack of atoms. Another option could be using quantum swap gates to implement quantum wires, each swap gate would be made up of three CNOT gates, but this would generate errors in the physical qubits that would generate additional error correction overheads.

Quantum teleportation uses error-free exchange quantum gates to distribute qubits in an undefined state between the source and destination of the cable or transmission medium. This undefined state is represented by a vector of qubits with probabilities equally distributed between bits 1 and 0. These qubits in the undefined state are intertwined, so having the measurement of a single qubit would give us the state of all the qubits of the vector.

It is easy to check for errors under this undefined state, regardless of the Qubit being transmitted. If an overload of errors occurs over the undefined state, they can be discarded with little damage to the transmission process. Once an undefined state exists at both ends, the qubits of the undefined state teleport the physical qubit across the required distance.

CODE QUANTUM TELEPORTATION

Quantum teleportation can also provide a general mechanism for performing quantum operations simultaneously while transporting quantum data. Performing calculations before executing the desired operation on the undefined states forms a kind of "quantum software" that automatically performs its operation on the teleported data. We can use this mechanism to perform optimization by converting between different error correction codes during teleportation. Specifically, we chose Steane's bug-fixing code for its ease of implementation, not its compactness. However, quantum memories only perform measurement and error recovery tasks, but not computation. Therefore, they can use more compact code that sacrifices some ease of computation.

Conversion between codes usually generates errors, but teleportation performs code conversion without a single physical quantum error compromising the entire state of a logical Qubit. Therefore, the proposal allows the logical Qubits to be efficiently stored in a compact error-correcting code by using teleportation during transmission to the quantum arithmetic logic unit (ALU) for conversion to a less compact error-correcting code, but more easily computable. From a conceptual point of view, this process is just a slight modification of standard quantum teleportation.

As Figure 3 shows, the specialized hardware generates an undefined state, sends one Qubit through the encoding mechanism for the source error correction code, and sends the other Qubit through the encoder for the destination error correction code.

The sender and receiver perform Qubit logic operations equivalent to teleportation at each end of the entangled pair. To implement a more robust form of this process, the underlying architecture could use stabilizing measurements to generate the appropriately encoded undefined states before teleportation.

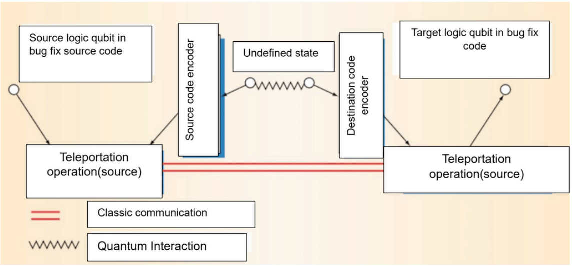


Figure 3. Proposed architecture for teleportation of quantum codes.

DYNAMIC PLANNER

The architecture uses a full classical high-performance processor for control. This processor runs a dynamic programming algorithm that takes logical quantum operations, interspersed with classical control flow constructs, and dynamically translates them into physical operations of individual Qubits. The algorithm uses knowledge about the global size of the input data and the physical error rates of the Qubits to construct dynamic programming that controls the quantum ALU, code teleportation, and refresh units of the Qubits' RAM. This is a lot of work for a single classic processor. We expect to have processors with much faster clock speeds, but it may be necessary to run multiple classic processors in parallel. The classical processor is essential for a quantum architecture to be efficient. We could run all quantum algorithms with the maximum error correction available, but doing so would be incredibly inefficient. Additionally, the use of dynamic compilation and knowledge of an algorithm's execution time make several performance optimizations available for computation, including application-specific clustering prior to error measurement. (Oskin, 2002)

CONCLUSIONS

Quantum computing represents a revolutionary paradigm in the field of computing, promising a radical change in processing and problem-solving capacity.

Its unique properties, such as superposition, which allows the Qubit to exist in multiple states simultaneously, and entanglement, which instantly links the states of multiple Qubits, offer unprecedented massive processing power and information storage capacity.

Today, advances in quantum computing are constantly evolving. Significant milestones have been achieved in the development of more stable and reliable Qubits, as well as in the construction of more scalable quantum systems. Companies, research institutions and governments are investing heavily in this area, which has led to the creation of increasingly powerful and accessible quantum computers.

Despite these advances, quantum computing still faces significant challenges, such as correcting quantum errors and building quantum systems large enough to be truly useful in practice. However, the transformative potential of quantum computing is undeniable, and it is expected to continue to be an exciting and promising field for the foreseeable future.

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