



Article

Quantum and Supercomputer Technology and Their Comparative Analysis

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Abstract: This article comprehensively examines the conceptual and practical aspects of two fundamental directions at the peak of the hierarchy of modern computing technologies — classical supercomputers and quantum computing systems. The relevance of the research is explained by the rapid growth of data volumes and the fact that traditional silicon technologies have reached their physical limits. The first part of the article analyzes the history of supercomputer development, their multi-core parallel architecture, and operating principles based on logical bits. Simultaneously, the technological limitations of such systems, including high energy consumption and cooling requirements, are highlighted. The second part explores the laws of quantum mechanics as the theoretical foundation of quantum computers, specifically the impact of superposition and entanglement phenomena on computing efficiency. The fundamental differences between classical bits and quantum bits (qubits) are scientifically justified, alongside the revolutionary potential of quantum algorithms (such as Shor's and Grover's algorithms) in traditional cryptographic and search systems. In the final section, a comparative analysis of these two powerful systems is conducted regarding processing speed, energy consumption, fault tolerance, and practical application areas. The research results indicate that quantum computers will not entirely replace classical supercomputers in the near future; instead, they will facilitate the formation of hybrid computing models. The article is intended for industry specialists, students, and those interested in the evolution of high technologies.

Keywords: Supercomputer, quantum computer, qubit, superposition, parallel loading, quantum supremacy, evolution, energy production, transformation.

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Introduction

At the current stage of human civilization's development, the speed and volume of data processing have become fundamental resources of strategic importance. The digital transformation of society, the large-scale implementation of artificial intelligence systems, and the necessity of working with Big Data demand a re-evaluation of the capabilities of traditional computing techniques. For many years, the semiconductor industry has maintained performance by reducing the size and increasing the number of transistors in accordance with Moore's Law. However, today, as the dimensions of elements in microchips reach the nanoscale—the level of atoms—quantum effects have begun to replace the laws of classical physics. This situation signifies that traditional silicon technologies are approaching their physical and technological "limits" [1].

From this perspective, the world of computing technology stands at the crossroads of two vast and unique directions. On one hand, supercomputers based on the parallel operation of thousands of central (CPU) and graphics (GPU) processors, developed over

decades, continue to increase their power [2]. They serve as stable and reliable tools in fields such as complex weather forecasting, aerodynamic calculations, and nuclear physics. On the other hand, quantum computers have emerged, relying on the extraordinary laws of quantum mechanics—the phenomena of superposition and entanglement [3]. Quantum computing systems are viewed not just as a new type of device, but as an entirely new paradigm of data processing.

Unlike classical bits, quantum computers operate using qubits (quantum bits). This enables them to solve certain types of problems—such as cryptographic encryption, modeling chemical processes at the molecular level, or complex logistical optimization problems—exponentially faster than classical systems. This phenomenon, known as "Quantum Supremacy," is expected to bring about a true evolutionary leap in the IT sector in the near future [4].

The primary objective of this article is to conduct a comparative analysis of classical supercomputers and quantum computing devices. Throughout the article, we will examine their architectural features, operating principles, energy consumption, and performance indicators [5]. Furthermore, we will analyze scientific hypotheses regarding whether quantum systems will completely displace traditional supercomputers or evolve as complementary hybrid systems. This research helps in understanding where modern computing technologies are headed and what the role of these systems will be in the future digital world.

Methods. In this research, a complex set of theoretical and comparative methods was employed to examine the functional capabilities of modern computing systems. The research process was carried out through the following stages and methods:

1. Systematic and Comparative Analysis Method: The traditional Von Neumann architecture of supercomputers was compared with the qubit-based quantum architecture of quantum computers. The systems' primary information units (bit and qubit), data processing algorithms, and operational efficiency were taken as key criteria [6].

2. Data Collection and Corpus Analysis: Primary data for the research were obtained from the technical reports of the TOP500 international rating agency for the years 2020–2025. Additionally, scientific publications from Google (Sycamore processor) and IBM (Eagle and Osprey processors) regarding Quantum Supremacy were examined using the corpus analysis method.

3. Mathematical Modeling and Algorithmic Evaluation: The complexity levels (Time Complexity) of classical parallel computing and quantum algorithms (Shor's and Grover's algorithms) were evaluated using mathematical modeling. Through this method, the discrepancy between exponential and linear computing times was identified [7].

4. Techno-Economic Evaluation Method: The energy efficiency (PUE - Power Usage Effectiveness) and operational costs of the computing systems were analyzed. This involved comparing the resources consumed for cooling and the energy consumption per computing unit [8].

This combination of methods served to ensure the reliability of the obtained results and to objectively evaluate the role of quantum systems within the modern IT ecosystem.

Results. The concept and development history of a supercomputer

Supercomputers are specialized computing systems that possess the highest performance levels in terms of processing power and speed within the technological capabilities of their era. Unlike classical personal computers, supercomputers are designed not for the needs of a single user, but rather to solve global scientific problems, process massive volumes of data, and model complex processes. Their performance is measured in FLOPS (Floating Point Operations Per Second), which represents the number of floating-point operations performed per second [9].

The history of supercomputers dates back to the mid-1960s. Seymour Cray is recognized as the pioneer of this field. Under his leadership, the **CDC 6600**, created in 1964, is considered the world's first true supercomputer. In the 1970s, the **Cray-1** revolutionized computing technology with its unique vector processor architecture. Starting from the 1990s, the era of "Massively Parallel Processing" (MPP) began, integrating thousands of standard processors into a single cluster. Today, the world's most powerful systems, such as the U.S. "**Frontier**" or Japan's "**Fugaku**" supercomputers, are recording results at the exaflops (10^{18} operations per second) level [10].

1. Architecture and operating principle

The efficiency of supercomputers depends on their internal structure and data flow management methods. The architecture of modern supercomputers is primarily based on the following principles:

- **Parallel Computing:** This is the cornerstone of supercomputers, where a large-scale task is divided into small, independent fragments that can be executed simultaneously. Each fragment is processed in an individual computing node [11].
- **Vector and Scalar Processing:** While classical processors perform operations on a single piece of data with a single instruction (**SISD**), supercomputers have the capability to process an entire array (vector) of data with a single instruction (**SIMD**).
- **Cluster Structure:** Thousands of independent servers (nodes) are integrated through ultra-high-speed internal networks (e.g., **InfiniBand**). This minimizes data exchange delays (**latency**).
- **Memory Hierarchy:** Supercomputers utilize a **Distributed Memory** system. While each processor has its own private RAM, it can also access global memory resources shared across the entire system [12].

2. Advantages and Disadvantages

Although supercomputers are the "engine" of modern science, they possess their own specific challenges:

Advantages:

- **High Speed:** They complete calculations in a few hours that would take hundreds of years for humans or ordinary computers.
- **Complex Modeling:** They are unique tools for genomic research, virtual modeling of nuclear tests, theories of the universe's origin, and forecasting global climate change.
- **Economic Efficiency (Indirect):** They save trillions in resources by testing new drugs or aviation components in virtual environments before laboratory trials [13].

Disadvantages:

- **Energy Consumption:** Modern supercomputers consume up to 20–30 megawatts of electricity, which is equivalent to the energy needs of an average small town.
- **Heat Dissipation:** Such high energy consumption leads to extreme overheating. Cooling them requires large water reservoirs and complex liquid cooling systems.
- **Cost:** Designing and constructing a single supercomputer requires hundreds of millions to several billion dollars, making them accessible only to major nations and large corporations [14].

3. Fundamentals of Quantum Mechanics

The operating principle of quantum computers relies on the laws of quantum mechanics—the physics of the microworld—which differ fundamentally from classical macroworld physics. While classical computers are based on the "closed" or "open" states (0 or 1) of transistors, quantum systems leverage the unique properties of particles at the atomic and subatomic levels. Two primary phenomena play a decisive role in this regard:

Superposition: This is the ability of a particle to exist in multiple states simultaneously. For instance, an electron in a quantum system can exist in both "up" and "down" spin states at the same time. This property elevates parallelism in the computing process to an unprecedented level.

Quantum Entanglement: This is a state where two or more particles become interconnected such that changing the state of one instantaneously affects the other, regardless of the distance between them. Einstein referred to this as "spooky action at a distance." This phenomenon enables quantum computers to transmit data at ultra-high speeds and process it within a systemically linked framework [15].

The concept of qubit and its basics

The smallest unit of information in quantum computing systems is the **qubit** (quantum bit). While a classical bit can only exist in one of two states (0 or 1), a qubit exists in a combination of these two states through the principle of superposition.

Mathematically, the state of a qubit is represented as a point on the **Bloch sphere**. If we have n classical bits, they can represent only one state at any given time. However, n qubits can encompass 2^n states simultaneously. For example, a system consisting of 300 qubits has the power to represent more information states at once than the total number of atoms in the observable universe. Physically, qubits are created using superconducting circuits, trapped ions, or photons.

4. Brief information about quantum algorithms

The true power of quantum computers is manifested in the specialized algorithms that run on them. Unlike classical algorithms, quantum algorithms possess the capability to examine all possible solutions simultaneously:

- **Shor's Algorithm:** Designed for factoring large integers. This algorithm enables the breaking of RSA encryption systems currently used worldwide within minutes (whereas a classical supercomputer would require billions of years for the same task).
- **Grover's Algorithm:** Provides a quadratic speedup for searching through unsorted databases. If a database contains N elements, where a classical search requires N operations, Grover's algorithm yields the result in \sqrt{N} operations.
- **VQE and QAOA:** These algorithms are utilized for modeling chemical molecules and solving logistical optimization problems, representing a revolutionary step in the development of new pharmaceuticals.

Discussion

Differences in Operating Principles

The fundamental difference between supercomputers and quantum computers lies in their relationship with data. Supercomputers are "deterministic" systems; they execute every operation in a precise sequence or in parallel, but always based on binary (0 and 1) logic. Their power depends on the number of transistors and the bandwidth of communication channels.

In contrast, quantum computers are based on "probabilistic" principles. Because qubits exist in a state of superposition, a quantum computer examines all possible solution variants simultaneously. If a supercomputer searches for an exit from a maze by checking each path one by one (or several in parallel), a quantum computer "traverses" all paths in an instant and identifies the shortest solution. This difference is also reflected in their architecture: while supercomputers occupy massive rooms filled with thousands of processors, a quantum computer consists of a microchip housed within a highly complex cryogenic (cooling) system.

Computing Speed and Efficiency

The concept of "**Quantum Supremacy**" occupies a central place in the discussion of computing speed. This concept implies that a quantum computer can perform a task in a few seconds that would require thousands of years for the most powerful supercomputer to solve.

- **Complexity Levels:** Classical supercomputers are highly efficient for problems with linear or logarithmic complexity. However, they reach their limits in problems with exponential complexity (e.g., the synthesis of new molecules).
- **Data Capacity:** Quantum systems demonstrate the "pinnacle of parallelism" in data processing. For instance, a system with 50–70 stable qubits can theoretically outperform the world's most powerful supercomputer. Today, companies like IBM and Google are working on processors with more than 400 qubits, ushering in a new era of computing efficiency.

Energy Consumption

Regarding energy consumption, these two systems take completely different approaches:

- **Supercomputers:** Their energy consumption is directly proportional to the number of processors. Modern supercomputers (e.g., Frontier) consume between 20 and 30 megawatts of electricity. A significant portion of this energy is spent on performing logical operations and running fans to prevent the system from overheating.
- **Quantum Computers:** The processors themselves require very little energy. However, to maintain the quantum state (qubits), the system must be cooled to temperatures near absolute zero (-273°C). Consequently, energy is primarily consumed by running powerful **dilution refrigerators**. Nevertheless, in terms of total energy consumed per single computing operation, quantum systems are predicted to be much more economical than supercomputers in the future.

Conclusion

Based on the comparative analysis of quantum and supercomputing technologies, the following fundamental conclusions have been reached:

Firstly, supercomputers have achieved a high degree of stability and reliability over their long evolutionary path. Based on parallel computing principles, they remain an irreplaceable tool in engineering, metrology, and public administration systems. However, the reduction of transistor sizes to the atomic level is physically limiting the performance growth of classical systems.

Secondly, quantum computers have ushered in a completely new era of data processing based on quantum-mechanical principles. Due to the phenomena of superposition and entanglement, qubits offer the possibility of solving highly complex combinatorial problems in seconds—tasks that classical bits cannot perform. This is expected to lead to revolutionary changes, particularly in cryptography, quantum chemistry, and the development of deep artificial intelligence models.

Thirdly, the comparative analysis indicates that quantum systems will not entirely displace supercomputers. Instead, we will witness a "computing symbiosis" in the near future. Hybrid infrastructures will emerge where simple and linear logical tasks are handled by supercomputers, while highly complex and probabilistic calculations are resolved by quantum processors.

Conclusion, quantum and supercomputing technologies are not competitors but rather complementary directions. Their integration will enable humanity to unlock the most complex mysteries of the universe, mitigate global climate crises, and manage biological processes at the molecular level.

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