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Quantum computers: where physics meets computer science

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Summary

Quantum Physics is defined as "the study of matter and energy at the most fundamental level". It has entirely transformed our perspective of the physical world and is also the foundation of numerous technological advancements. More specifically, quantum mechanics has been applied in sectors such as medicine and biology, with quantum computing emerging as the most prominent among them. [5] The primary objective of this study is to analyse the concepts of quantum computing, focusing on what quantum computers are, how they function, as well as outline and explain the differences between them and standard computational models (classic computers). Furthermore, their relation to the laws of physics will be discussed. Secondarily, this article aims to provide recent achievements, such as existing quantum computers and plans concerning the future so as to underline the role quantum physics will play, shaping the frontier of computation.

1. Computers and computer science

1.1 Classical computers

A computer is an electronic device that processes data according to instructions provided by software programs. It takes input (data), processes it using a central processing unit (CPU), stores information, and produces output (results) to perform various tasks. [8] A classical computer is a type of computer that uses bits. [11]

1.2 Bits

A bit (binary digit) is the smallest unit of data that a computer can process and store. It can take only one of two values: 0 or 1. 0 signifies the absence of electricity while 1 its presence. These bits create binary strings (sets of ones and zeros) that are translated into low level programming languages (usually assembly) and are then converted into high-level programming languages that are more easily used by humans in order to create programs that will satisfy their needs. [11], [9]

1.3 Logic gates

Logic gates are electronic circuits – the fundamental building blocks of a computer. The output of the logical operations performed will be either 0 or 1, as the input is also the value of a bit. We can therefore say that logic gates manipulate bits, changing them to the desired value each time. In classical computers there are 8 main types of logic gates, which use Boolean algebra and basic mathematic operations (algebraic functions). Logic gates can be represented either by using graphic symbols or truth tables, where their inputs and outputs are included (in the representation). [10]

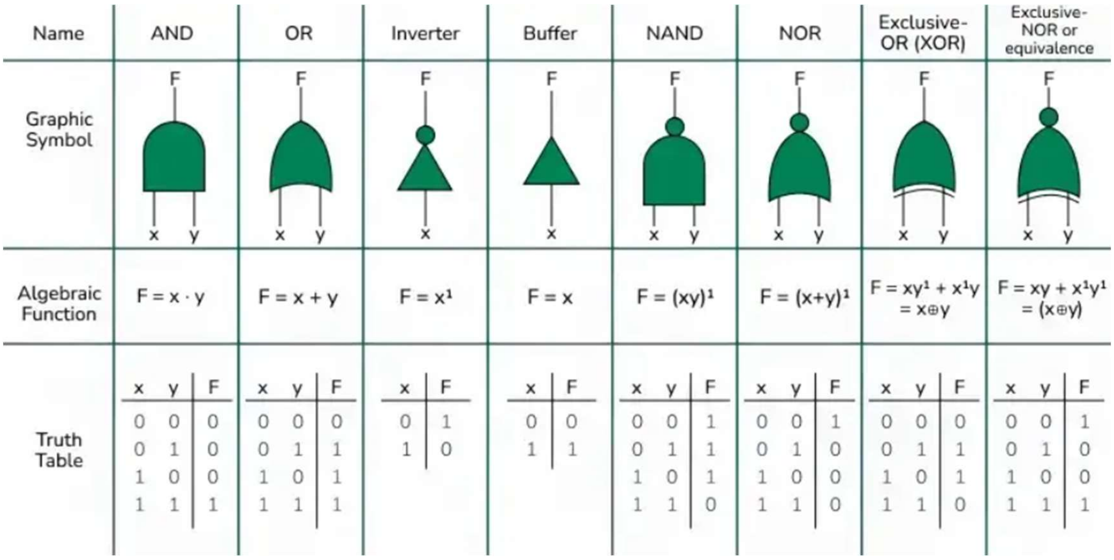

Figure 1: Classic Logic gates

2. Quantum mechanics

2.1 Quantum computing

Quantum computing is an emergent field of computer science and engineering that harnesses the unique qualities of quantum mechanics to solve problems beyond the ability of even the most powerful classical computers. [3], [12]

2.1.1 Quantum computers

Quantum computers are advanced machines based on quantum mechanics. They can perform tasks previously considered impossible due to their high compilation time in classical computers. [13], [6]

2.1.2 Qubits

Qubits or quantum bits are basic units of information in a quantum computer, just like bits are the building blocks of classical computers. Qubits are symbolized using Dirac notation: $|0\rangle$ (ket 0) and $|1\rangle$ (ket 1). They are states, not fixed values, hence they can also be symbolized using vectors. Before measurement, quantum bits are in superposition of values, meaning that they can exist in both 0 and 1 states simultaneously. Only after the measurement collapses they take their final value. [14], [12], [2]

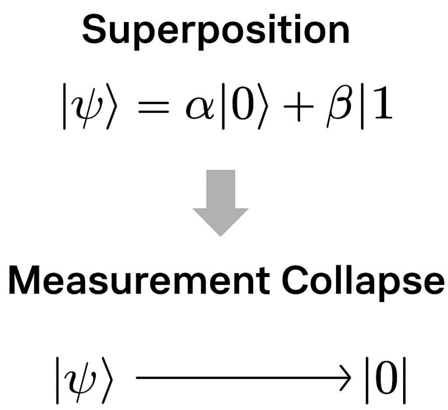

Figure 2 Representation of a qubit in superposition

In figure 2, |0⟩, |1⟩ are the qubit's basis states (like 0/1 bits), with α,β being complex probability amplitudes[1]. [4] Their squared magnitudes give us the probabilities of measuring either 0 or 1. After measurement, the qubit collapses into a certain value (0 or 1). [14]

Qubits can also be represented as a point on a sphere (Bloch Sphere). |0⟩ is put at the "north pole" of the sphere, |1⟩ at the "south pole" while any other point on the sphere represents a qubit in superposition of values. [14]

2.1.3 Quantum logic gates

Just like its classical analogue, qubits can be manipulated using quantum logic gates. Quantum logic gates are simple unitary operations on qubits. As mentioned above quantum states can be mathematically represented in the form of vectors. Similarly, quantum logic gates are represented using matrixes. So, in order to calculate the outcome a quantum logic gate will have on a quantum state one should multiply the vector representing the qubit's state with the quantum gate's matrix. [4], [14], [2]

2.1.4 Quantum error correction

We define noise as everything that causes a quantum computer to malfunction. Due to noise, all the information stored in the qubit might get degraded. This loss of information is called decoherence. Quantum computers are extremely sensitive so as a result the quantum state of a qubit might be erased or doesn't end up where one would expect. Quantum error correction refers to all the algorithms that aim to fix errors in a quantum computer's algorithm. Creating a useful error correction algorithm is extremely hard as spreading information between qubits takes really long. [16]

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[1] Describe the likelihood of finding a quantum system in a particular state, they're not probabilities themselves

2.2 Laws of quantum physics applied

2.2.1 Superposition

Superposition is the term that states that a quantum system can exist in a combination of multiple possible states at once. [12]

2.2.2 Entanglement

Quantum entanglement is the phenomenon that occurs when two or more objects become linked in such a way that they behave as a single system, even when separated by large distances. In other words, it is the correlation between two or more particles such that the state of one instantly affects the state of the others, no matter the distance. [12], [7]

2.2.3 Interference

Quantum interference is a phenomenon in quantum mechanics that arises from the wave-like nature of quantum particles such as electrons or photons. Different states of a particle interfere with each other when in superposition. Similarly, quantum probability amplitudes can add (constructive interference) or cancel (destructive interference). [15], [12]

2.2.4 Decoherence

Decoherence is a process in which a quantum system loses its quantum properties (superposition/entanglement) as a result of interacting with its surrounding environment. [17], [12]

2.3 Existing models/future plans

One major milestone in quantum computing was Google's achievement in creating a quantum processor, the sycamore. Sycamore, as well as other quantum computers, mostly from Asian companies (Zuchongzi 2.0/Zuchongzi 2.1, photon- based quantum computers) have no real practical utility for society and were just created to study the difference in compilation time between classical and quantum computers. On the other hand, quantum computing will be the beginning of new, life-changing technological advancements. The computing models mentioned above were compared with *Summit*, the fastest supercomputer in the world. The results are showed in figure 3. The differences in compilation time are huge. [1], [18]

TABLE II. Performance comparison of tensor network algorithm runtimes for various circuits on *Summit* supercomputer. With estimated classical simulation consumption for the random quantum circuit sampling experiment on Sycamore, Zuchongzhi 2.0, and Zuchongzhi 2.1 quantum processors is included [38].

Parameters	Google's Sycamore Quantum AI vs Zuchongzhi Quantum Processors			
	Sycamore [33]	Zuchongzhi 2.0 [37]	Zuchongzhi 2.1 [38]	Zuchongzhi 2.1 [38]
Quantum Circuit	53-qubit 20-cycle	56-qubit 20-cycle	60-qubit 22-cycle	60-qubit 24-cycle
Estimated Runtime on *Summit*	~~10,000 years~~ 15.9 days[a]	8.2 years	4,800 years	48,000 years
Runtime on Quantum Computer	3 minutes[b]	72 minutes	60 minutes	252 minutes
Fidelity	0.224%	0.0662%	0.0758%	0.0366%

[a] Google's estimations projected that the task would demand an astounding 10,000 years for *Summit*, the most powerful supercomputer. Subsequently, IBM provided a contrasting perspective, asserting that *Summit* could accomplish the same task in a matter of days [38, 62].
[b] As reported by Google's Quantum AI and Collaborators in [33], while the time estimated for performing the task in [38] was 600 seconds.

Figure 3: Summit vs quantum processors

In the future, quantum computers will impact existing technologies as well as lead us to the achievement of new technological advancements. Long-lasting batteries as well as effective medicines will be created and the environment (reduction of emissions) will be impacted. Quantum computers will also contribute to existing technologies including machine learning and the discovery of new algorithms such as error correcting codes. Lastly, they will themselves be used as tools, similarly or not to classic computers. [19]

3. Conclusions

Quantum computing demonstrates how quantum physics and computation collide. This article refers to qubits, superposition, entanglement, and quantum gates as principles of quantum computing. Despite some limitations, according to research, quantum technologies will play an important role in future innovation.

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