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Quantum Computing: Unleashing the Potential of Qubits and Quantum Gates

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Abstract**—** The potential of quantum computing to revolutionize various industries and markets has been widely recognized. By utilizing the principles of quantum mechanics such as superposition and entanglement, quantum computers are capable of representing data and performing operations on them at an unprecedented speed. These unique features allow for solving complex problems that are practically impossible for classical computers to solve efficiently. This article provides an overview of the three layers of a quantum computer, which include the hardware layer, system software layer, and application layer. Moreover, it discusses the potential applications of quantum computing and explores possible research directions in the field of information systems.

Keywords**—**Quantum Computing, Qubits, Quantum mechanics, gates

I. INTRODUCTION

The potential of quantum computing to disrupt industries and markets is widely acknowledged. According to a recent McKinsey report, the global market value of quantum computing is expected to reach USD 1 trillion by 2035, particularly in industries such as finance, chemistry, pharmaceuticals, and automotive (Hazan et al., 2020). Leading technology companies such as Google, IBM, Microsoft, Amazon, and Alibaba are investing billions in the research and development of quantum computing and offer partial access to their quantum computers through cloud infrastructures. Governments are also investing heavily in quantum computing, with China investing USD 10 billion in a national quantum computing laboratory, the US government providing USD 1 billion, and the EU having an overall budget of more than EUR 1 billion (Castelvecchi, 2018; Deicker & Yasiejko, 2018).

II. RELATED WORKS

The principles of quantum mechanics, such as superposition and entanglement, are harnessed by quantum computers to represent data and perform operations on them (Ding & Chong, 2020). These principles allow quantum computers to solve complex problems much faster than classical computers.

In contrast to classical computers that process hypotheses sequentially, quantum computers have the ability to calculate and test multiple hypotheses simultaneously (S.-S. Li et al., 2001). Additionally, certain quantum algorithms can be designed to solve complex problems in significantly fewer steps compared to classical algorithms, resulting in lower complexity (S.-S. Li et al., 2001). Due to this capability, quantum computing has the potential to bring a significant breakthrough in modern IT in the coming years and even trigger the transition towards the "5th industrial revolution" (Hadda & Schinasi-Halet, 2019).

Experts predict that quantum computing, despite its current state of development, could offer unprecedented advantages, particularly in optimization, artificial intelligence, and simulation. It is expected that simulations of molecules will be among the first real-world applications of quantum computers, as molecules obey the laws of quantum mechanics. Industries such as finance, transportation and logistics, global energy and materials, meteorology, and cybersecurity are also likely to benefit from quantum computing. However, there are still many unresolved challenges in physics and computer science related to hardware architectures, data management, application software, and algorithms, requiring fundamental research in these areas and beyond. (Langione et al., 2019; Ménard et al., 2020; Gerbert & Ruess, 2018; Almudever et al., 2017).

III. QUANTUM COMPUTING ARCHITECTURE

Paul Beniof introduced the idea of a quantum touring machine, or a quantum computer, in 1980. Richard Feynman proposed the first practical use of a quantum computer in 1982, which was the efficient simulation of quantum systems. Quantum computers are universal computing devices that store information in quantum bits (qubits) and transform them using specific principles of quantum mechanics. Quantum computing is a computation that collects different states of qubits, including superposition, interference, and entanglement, to perform calculations. Unlike general-purpose computers, quantum computers are specialized devices designed to solve specific tasks much faster than classical computing. Quantum computers will require classical computers to load input/output data, retrieve computation results, and control the quantum computer's electronic and internal processes.

The combination of quantum and classical computers creates a quantum computing system that enables quantum computing to take place. To illustrate the essential mechanisms and components of a quantum computing system, we use the model developed by Ding and Chong (2020), which is based on an analytical separation of the key components into hardware, system software, and application. This model allows for a conceptual view of computing architectures.

Our sources of expertise differentiated between comparable layers in their interviews to elucidate the current state of the art, the obstacles faced by contemporary organizations, and the operation of quantum computing systems. This differentiation was made either through the use of the layered modular architecture of digital technologies or through the classification of Platform-as-a-Service and Software-as-a-Service. Figure 1 depicts a quantum computing system, which comprises a van Neumann architecture for classical computing and a three-layer architecture for quantum computing.

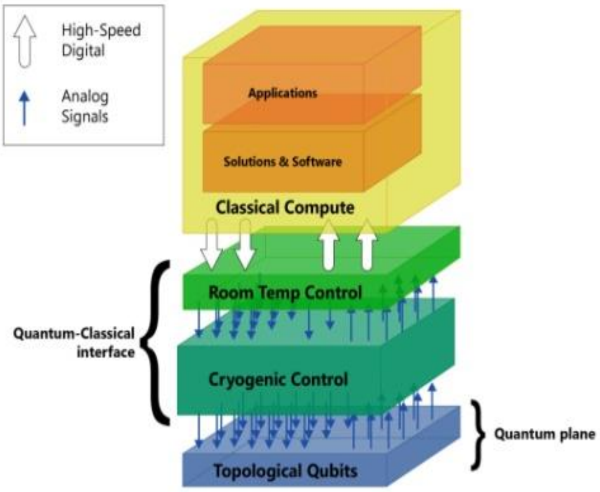


Fig. 1 Architecture of Quantum Computing

Hardware Layer

Classical and quantum computers differ fundamentally in the way they store information. While classical computers use bits to store information, which can only have a value of either zero or one, quantum computers use qubits (quantum bits) which can simultaneously hold any linear combination of zero and one due to the unique properties of quantum mechanics. This ability to exist in multiple states at once is known as superposition (refer to visualization in Fig. 2) and is a key advantage of qubits(Steane,1998).

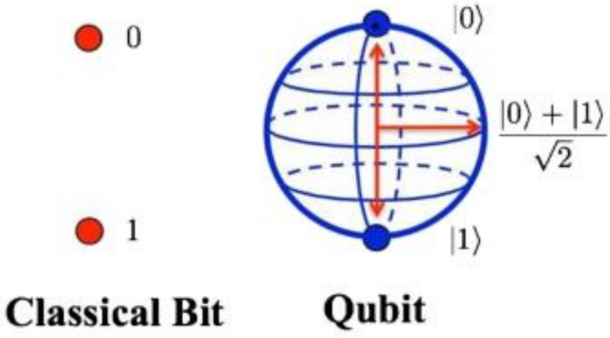


Fig.2. Classical Bit and Qubit

Superposition refers to the probabilistic nature of qubits, where they are described by the probability of being either zero or one rather than a distinct value. For instance, a qubit can have a 60% probability of being zero and a 40% probability of being one. However, once measured, the qubit collapses to a single classical value of either zero or one. This is a crucial property of qubits(Bosch,2020 and Ding & Chong, 2020). The superposition property of qubits enables a quantum computer with just four qubits to represent 16 four-digit numbers simultaneously, with the number of representable states doubling with each additional qubit. In contrast, a classical computer with a sequence of four bits can only represent a single four-digit number.

The true advantage of quantum computing lies in its ability to perform an exponential number of calculations simultaneously. Although only one calculation's solution can be read at the end of every program, a quantum algorithm can be designed to increase the likelihood of obtaining the desired final result. For instance, if we want to determine whether any rare turbulence could cause a plane to crash, a quantum algorithm can help in finding the answer with greater accuracy.

Quantum computing possesses not only qubits but also the property of entanglement, which is a feature of quantum mechanics. Entanglement occurs when the state of one qubit is dependent on the state of another qubit, resulting in a change to the other qubit when one qubit undergoes any flip or rotation. Even when the entangled qubits are separated by a significant distance, their states collapse to either one or zero (depending on their probabilities) when either one of them is measured(Einstein,1935 and Schrödinger, 1935). The advantage of entanglement is that when a qubit influences the other qubits around it, all work together in harmony to reach a solution.

Analog quantum computing involves the gradual transformation of the quantum state through quantum operations to produce an output that closely matches the desired answer. Adiabatic quantum computers are one example of analog quantum computing that aims to build a universal quantum computer. Quantum annealing is a specific type of adiabatic quantum computing that uses algorithms and hardware to solve computational problems by evolving towards the ground states(Albash and Lidar,2018 and Vinci & Lidar,2017).

To manipulate the information encoded in qubits in digital gate-based quantum computing, digital gates are utilized. This is different from the analog approach where the natural evolution of quantum states is sampled to find the optimal state of low energy. In digital gate-based quantum computing, the evolution of the quantum states is actively controlled to find the best solution, making it much more flexible. As a result, it can be used to solve large classes of problems, unlike quantum annealing (which is a special form of adiabatic quantum computing).

System software layer

The layer of system software is constructed upon the hardware layer, directing the system's operations to harness the capabilities of qubits, including superposition and entanglement. The software layer confronts the obstacles of thermodynamically volatile quantum states, working to minimize thermal interference both within and outside of the quantum system and carrying out error correction processes.

Quantum computing is susceptible to numerous potential sources of noise. For instance, digital gate-based and other quantum computers are highly responsive to variations in the surroundings, such as temperature fluctuations and vibrations. Noise may also result from inaccurate control of the quantum hardware or manufacturing faults (Ding & Chong, 2020). Cooling chips to a temperature just a fraction above absolute zero is often necessary for the operation of many quantum computers. Given the inevitability of noise, the first stage of quantum computing is often referred to as the Noisy Intermediate-Scale Quantum Computer (NISQ, Preskill, 2018).

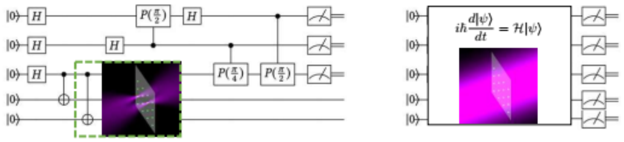
Application layer

Efficient quantum memory remains a key challenge for modern quantum computers, as it has yet to be satisfactorily resolved (Ciliberto et al., 2018). Although various theoretical proposals for constructing quantum random access memory (QRAM) exist, actually building such memory may prove challenging (similar to the challenge of constructing quantum computers themselves). However, recent research (Hann et al., 2019; Park et al., 2019) has suggested several possible approaches to QRAM construction. Presently, there is no effective method for storing qubit states in memory for extended periods of time for additional calculations. Thus, data must be transferred from a classical computer to the targeted quantum computer, and following the computation, states must be read (measured) by the classical computer before the qubits lose their information. The no-cloning theorem precludes the creation of copies of quantum states for computational use. The sole means of loading a quantum state from quantum memory to a quantum program necessitates a SWAP operation, which removes it from memory.

IV. METHODOLOGY

Neutral atom quantum processors (QPU) are capable of performing both digital and analog quantum processing tasks. In digital computing, quantum algorithms are broken down into a series of quantum logic gates, represented by a quantum circuit, as depicted in Fig. 3(a). The quantum gates are implemented by directing carefully calibrated laser pulses at a selected subset of individual atoms in the register. In analog computing, lasers are employed to create a Hamiltonian, with the qubits evolving in time according to the Schrödinger equation, as shown in Fig. 3(b). The final state of the system is measured by observing the state of each individual qubit. This section discusses the implementation of both digital and analog computing tasks.

For digital computing, qubits that are resilient to decoherence, i.e., weakly connected to their environment, are required. The two hyperfine ground states (F = 1 and F = 2) of rubidium atoms are ideal qubits for this purpose, since they exhibit very long lifetimes (on the order of tens of years), preventing radiative coupling with the electromagnetic environment. Laser beams are used to perform gates, as previously discussed. By strongly focusing the lasers, specific qubits can be accurately addressed, with the spacing between atoms in the register typically being several micrometers (as illustrated in the inset of the CNOT gate in Fig. 3(a)). Interestingly, a universal gate set can be created using only one- and two-qubit gates. For instance, the ability to achieve arbitrary single qubit rotations and the well-known two-qubit CNOT gate is enough to realize any quantum algorithm [15].



(a) (b)

Fig. 3: Digital- vs analog processing. (a) In digital processing, a succession of gates is applied to the qubits to implement a quantum algorithm. Each gate is performed by addressing the qubits individually with laser beams. (b) In analog processing the qubits evolve under a tailored Hamiltonian H, for instance by illuminating the whole register with a laser beam. The wavefunction |ψi of the system follows the Schrödinger equation.

V. RESULT & DISCUSSION

Qubits and quantum gates are the building blocks of quantum computers. Qubits are quantum-mechanical objects that can be in a superposition of two states, 0 and 1. Quantum gates are operations that can be performed on qubits, and they can be used to perform complex calculations that are impossible for classical computers.

Quantum computers have the potential to revolutionize many industries, including finance, healthcare, and materials science. For example, quantum computers could be used to develop new drugs, design new materials, and create new financial products.

The development of quantum computers is still in its early stages, but there has been significant progress in recent years. In 2017, Google announced that it had achieved quantum supremacy, which means that it had built a quantum computer that could solve a problem that would be impossible for a classical computer.

However, there are still many challenges that need to be overcome before quantum computers can be used for practical applications. One of the biggest challenges is decoherence, which is the tendency of qubits to lose their quantum properties due to interactions with the environment.

Another challenge is error correction, which is the process of detecting and correcting errors that occur during quantum computation. Error correction is essential for quantum computers to be able to perform accurate calculations.

Despite the challenges, the potential of quantum computers is enormous. Quantum computers could revolutionize many industries and solve some of the world's most challenging problems. As the technology continues to develop, we can expect to see quantum computers become more powerful and more widely available.

Here are some of the potential applications of quantum computers:

- Finance: Quantum computers could be used to develop new financial products, such as derivatives and options. They could also be used to model financial markets and predict future prices.
- Healthcare: Quantum computers could be used to develop new drugs and treatments. They could also be used to design new medical devices and to diagnose diseases.
- Materials science: Quantum computers could be used to design new materials with improved properties. They could also be used to study the behavior of materials at the atomic level.

These are just a few of the potential applications of quantum computers. As the technology continues to develop, we can expect to see even more applications emerge.

VI. CONCLUSION

In this article on quantum computing fundamentals, we present an overview of the main concepts involved. We also provide a brief explanation of the three layers of a quantum computer: hardware, system software, and application layer. Drawing on insights from leading experts in the field, we suggest several areas of focus for investigating the social and technical implications of quantum computing. As quantum computing is poised to disrupt various aspects of organizational and IS-related ecosystems, we anticipate significant impacts on academic research, industry practice, and education. However, we acknowledge that the field of quantum computing is still in its nascent stage and that much remains to be understood about this emerging computing paradigm.

CONFLICT OF INTEREST
No conflict of interest

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