Comparison of the Quantum and Conventional Algorithms: Evidence from Genetic Algorithm and Ant Colony Algorithm

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Abstract. Contemporarily, with the slow-down development speed of classical computing, quantum computing is becoming the focus of research as a replacing technique. It is a well-known approach that can offer exponential speed-up for a certain type of calculation issues based on the state-of-art optical facilities and techniques. In this paper, the development of quantum computing will be briefly introduced firstly. Subsequently, this paper will demonstrate the principle of different types of quantum algorithms as well as the realization scenarios. Afterward, the similarities, as well as differences between the conventional algorithms and the quantum algorithms in the genetic algorithm and ant colony algorithm, will be compared and analyzed. Based on the analysis, it is obvious that quantum algorithms are more powerful in solving specific problems compared with conventional algorithms, where the speed is much quicker than the traditional approaches. According to the results, it’s necessary to study the practical application of quantum algorithms. These results shed light on guiding further exploration of quantum algorithms.

Keywords: Quantum Algorithms; Genetic Algorithm; Ant Colony Algorithm.

1. Introduction

Electronic computers' computing power, storage capacity, and connection speed have all significantly increased, laying the groundwork for the growth of information technology in contemporary civilization. The demands for information processing speed are increasing as a society and the economy continues to advance. Nowadays, the development of classic microelectronics technology based on electron transmission has encountered a bottleneck. Moreover, the integrated density and transmission line width of the transistors has reached the ultimate level. Meanwhile, the limit of the traditional integrated circuit manufacturing process makes it impossible for the computing speed of classical computers to continue to develop in accordance with "Moore's Law" [1]. Above all, the classical computing has gradually entered the development dilemma. In 1981, scientist Feynman proposed the concept of quantum computers [2]. Quantum computing is based on the intersection of Quantum Mechanics and Computers. More importantly, its emergence makes it possible to end the limitations of quantum mechanics when devices are miniaturized. Besides, Peter Shor proposed the Shor Algorithm in 1994 [3]. In addition, Lov Grover proposed the Grover Quantum Search Algorithm back in the year 1996 [4]. Two years later, MIT and LANL realized quantum computing using liquid-state nuclear magnetic resonance [5]. These theories gradually build up the entire quantum computing system. At present, although quantum computers are still in the early stage of development, their application potential is huge, and quantum computers will replace today's classical computers in many tasks.

In recent years, quantum computing has developed rapidly. Many countries are involved in the development of quantum computing, and the research on quantum computing has been raised to the national level. Some IT companies are also promoting research on quantum computing. In addition, more and more quantum computing companies are emerging, and they have achieved good development results. D-Wave, as the world's first quantum computing company, has proposed a technology route that subverts the mainstream. The Quantum Simulate Anneal (QSA), through the quantum tunneling effect, achieves the purpose of acceleration, and finally developed a quantum annealing simulator [6]. Judging from the development process of classical computers, the development trend of quantum computers will accelerate the realization. Nowadays, more and more quantum cloud computing platforms are emerging. IBM has launched a quantum computing cloud service, provided the Qiskit quantum program development kit, and established a relatively complete open-source community [7]. Although the quantum computing cloud platform started late in China, its development momentum has been obvious in recent years. Huawei's HiQ quantum computing simulation cloud service platform, the number of qubits that can be simulated is increasing [8]. Moreover, Huawei has also developed a quantum programming framework compatible with ProjectQ [9]. Professor Seth Royd of MIT, together with a few other researchers, came up with the idea for the quantum algorithm that solves linear equation systems. It will only take 10s to solve the linear equation system using a quantum computer with a GHz clock [10]. In August 2016, Nature published an article introducing a programmable small quantum computer developed by the Joint Institute of Quantum Information and Computer Science (JQI) of the University of Maryland [11].

This study proposes to make a comparison between quantum algorithms and conventional algorithms to explain the advantages of studying the Quantum Algorithm. This work may provide a wide range of prospects for the future research on computers. The organization of the paper is as described below. The basic concept and the principle of the quantum algorithm are described in Section 2. The comparison between the Conventional Genetic Algorithm and Quantum Genetic Algorithm is presented in section 3. Section 4 presents how better the quantum algorithm is in solving the Traveling Salesman Problem. In the fifth section, this study summarizes the limitations of the current quantum computing and the outlook of its future research. At the end of the article, a brief conclusion is given in section 6.

2. Principle of Quantum Algorithms

A Quantum computer is a computing tool that uses the state of microscopic particles to store and process information. The basic principle is to prepare manipulative quantum states by physical means and to use quantum mechanically related properties, e.g., superposition and coherence of quantum states to operate, save and process information [12]. More recently, people have tried to prepare and control quantum states by means of physical manipulation, such as nuclear magnetic resonance, ion traps, quantum dots, and photons. Quantum algorithms refer to computational methods that run on quantum computers and use the principles of Quantum Mechanics to solve practical problems. Currently, there have been several types of research on quantum algorithms, which have successfully achieved major theoretical breakthroughs in computing performance relative to classical algorithms.

In order to process and save the data, traditional computers convert binary information into a form that can be understood by the potential of the very small transistors that are embedded in silicon chips. However, it does have certain drawbacks, such as the fact that each potential can only process and store one piece of data at a time, which can either be 0 or 1. Thus, only when multiple potentials work together can a complex operation process be completed.

On the contrary, according to the principles of quantum theory, a single quantum can be in a superposition of multiple orthogonal states simultaneously. Here, one usually takes two as an example for the superposition, such as the ground state and first excited state of electrons in hydrogen atoms, left-handed and right-handed circularly polarized light. The smallest unit of information storage is the quantum bit (qubit) in quantum computing. That means a qubit can be in a superposition of both states 0 and 1 or one of them in the same moment. Generally, a bit of quantum information can be expressed in the form of:

$$|\psi\rangle = a|0\rangle + b|1\rangle \tag{1}$$

Where $|0\rangle$ and $|1\rangle$ represent two mutually orthogonal standard states and correspond to the values of $|0\rangle$ and $|1\rangle$ under a classical bit, respectively. $|a|^2$ and $|b|^2$ are complex numbers satisfying:

$$|a|^2 + |b|^2 = 1 \tag{2}$$

The quantum state will collapse to $|0\rangle$ with probability $|a|^2$ and $|1\rangle$ with probability $|b|^2$. There are two typical quantum algorithms: Shor's algorithm and Grover's algorithm.

Shor's algorithm solves the prime factorization problem effectively, which is to find the prime factor of a decomposable positive odd number. This problem is equivalent to the factorial problem [13], which can be solved by a quantum phase estimation algorithm. For positive integers x and N that satisfy x < N and have no common factors, the order of x mod N is defined as the smallest positive integer r such that x^r = 1(mod N). The order problem is to determine the order for a particular x and N [13]. Usually, the register for storing the phase estimation result is called the first register, and the register for inputting the eigenvector $|u\rangle$ is called the second register. Fig. 1 shows the quantum circuit for solving the order problem using the phase estimation algorithm.

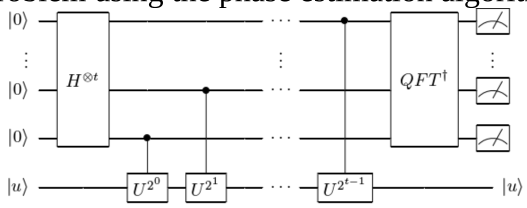

Fig. 1 The phase estimation algorithm solves the quantum circuit of the order problem. H is Hadamard Gate. U refers to the Unitary operator. |u⟩ refers to an eigenvector of the unitary operator U, the corresponding eigenvalue is $e^{2\pi i\varphi}$. The t is the qubit in the first register. $QFT^{\dagger}$ refers to Inverse Fourier Transform.

The quantum algorithm for finding order is just applying the phase estimation algorithm to the unitary operator:

$$U|y\rangle \equiv |\text{xy(mod N)}\rangle \tag{3}$$

The quantum state

$$|u_s\rangle \equiv \frac{1}{\sqrt{r}} \sum_{k=0}^{r-1} e^{\frac{-2\pi isk}{r}} |x^k \, mod \, N\rangle \tag{4}$$

Is an eigenvector of the unitary operator U

$$U|u_s\rangle = e^{\frac{2\pi is}{r}} |u_s\rangle \tag{5}$$

Using the quantum phase estimation algorithm, the estimated value of the phase φ =s/r can be obtained with high accuracy, and then the order r can be easily obtained.

In addition, one of the many benefits that quantum computers offer over traditional computers is the significantly increased speed with which they can scan databases. Grover's algorithm demonstrates this capability. The algorithm can be used for quadratic speedups on unstructured search problems. In addition, it can be used as a general trick or subroutine to obtain quadratic speedups for various other algorithms. Taking advantage of the parallelism of quantum computers, Grover's algorithm can perform a complete search in a limited search space, and can also use the amplitude amplification technique to measure the target solution.

3. Comparison of Conventional Genetic Algorithm (CGA) & Quantum Genetic Algorithm (QGA)

The Genetic Algorithm (GA), which is first proposed by Holland, is a type of evolutionary algorithm. It is based on Darwin's theory of biological evolution "survival of the fittest, survival of the fittest". The execution flow of GA imitates the complete process of biological evolution in nature, which is a relatively robust, random, and adaptable optimization process. Before the conventional GA starts to operate, it needs to generate an initial population according to the problem. The chromosomes of each individual in the population are encoded to execute the evolution strategy. After several evolutions, the individual with the highest fitness is selected. This is the optimal solution to the problem. A flow chart is shown in Fig. 2. The specific implementation steps of the CGA are as follows:

Select the relevant operating parameters population size N, chromosome length l, crossover probability pc, mutation probability pm, the maximum number of iterations G, and set the iteration count parameter to t = 0;

Generate the initial population as p;

Calculate the fitness of individuals in a population as F(x);

Use the selection operator to generate a new population;

According to the crossover probability, carry out genetic recombination by using the crossover operator;

According to the mutation probability, use the mutation operator to generate a new population;

Judge whether the termination condition is triggered, if not, then return to Step3 to continue running. On the contrary, the individual with the highest fitness is taken as the optimal solution, and the algorithm is ended.

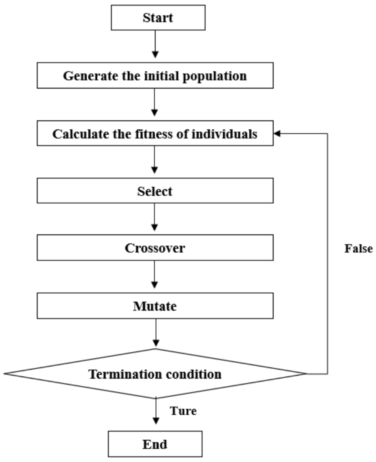

Fig. 2 Flow chart of CGA.

Quantum Genetic Algorithm (QGA), where the idea of quantum computing is added to the genetic algorithm, is an emerging algorithm for biomimetic evolution simulation. In 2000, Han and Kim proposed GQA, which integrated the superposition idea and representation method in quantum computing into the genetic algorithm, and proved its excellent global search performance [14]. In 2002, the two came up with a quantum-inspired evolutionary algorithm (QEA) based on GQA to solve the problem, which improved the disadvantage that GQA was prone to fall into local optimal solutions. In addition, they also verified the effectiveness and applicability of QEA for combinatorial optimization problems through the knapsack problem [15]. Talbi and colleagues came up with the idea for a quantum-derived genetic algorithm in 2004, and they developed it in 2004. This algorithm combined the quantum concept with the traditional genetic algorithm in order to find an accurate solution to the TSP problem [16]. An improved hybrid quantum-inspired genetic algorithm was used by Konar et al. in 2017 to handle real-time task scheduling in multiprocessor systems. The algorithm was inspired by quantum mechanics [17]. The same year, Silveira et al. proposed a new evolutionary solution for the sorting issue that was inspired by quantum mechanics. This solution was a step forward in the process [18].

The QGA symbolizes the chromosome with the appropriate quantum state, and the update evolution process is completed by the rotation of the quantum gate. This allows the quantum genetic algorithm to fully utilize the capabilities of quantum computing while inheriting the advantages of the CGA. It is a method for more effectively tackling optimization issues. A flow chart of QGA is illustrated in Fig. 3. The specific implementation steps of the QGA are as follows:

Determine a certain number of initial population Q(t), the population can be randomly selected, but the number should not be too large. Then, the method of qubit coding is used to construct chromosomes for the individuals of the undetermined population and encode them to obtain the population P(t), and record the evolutionary algebra as t=0;

Select a suitable fitness function, and compute the fitness value of every member of the population P(t). Evaluate the fitness state of the individual and record the individual with the best fitness, and store the obtained individual optimal fitness value in B(t);

Use the quantum gate update strategy to genetically mutate chromosomes, and record the evolutionary algebra value +1: t=t+1;

Use the fitness function again to calculate and evaluate the mutated individual fitness value, compare the optimal value with B(t), and store the optimal value if it is better than B(t);

Judgment of algorithm termination condition: if the termination condition is met, end the algorithm, save and output the current optimal solution b, otherwise go back to (3) to continue the algorithm.

Both QGA and CGA are parallel swarm intelligence optimization algorithms. Through the following comparison, one has a further understanding. The similarities and differences between the two algorithms are shown in the Table. 1.

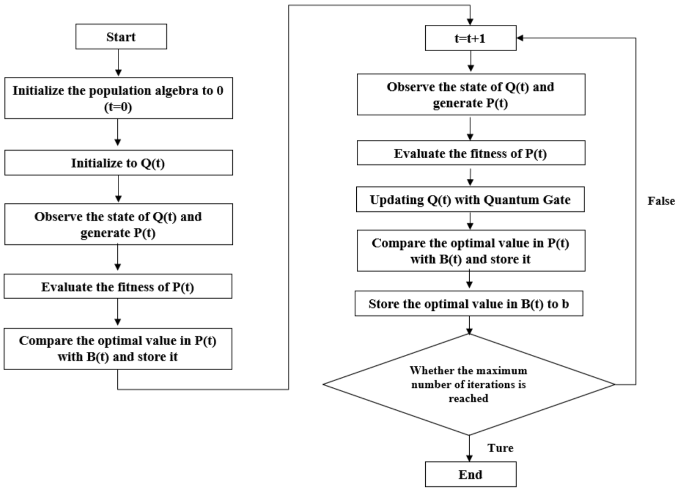

Fig. 3 Flow chart of QGA

Table. 1 Comparison of GA and QGA optimization operations.

		CGA	QGA
Differences	Initialization	Generated population randomly	$\|\phi_{q_i}^0 >= \sum_{k=1}^{2^m} 2^{-m/2} \|s_k >$
	Decoding	Decoding formulae	Generate binary solution set directly
	Population renewal	Selection, Crossover, Mutation	Quantum revolving gate
Common	Global optimization algorithms		
	Implicit parallelism		
	Random search algorithm		

4. Comparison of Ant Colony Algorithm (ACA) and Quantum Ant Colony Algorithm (QACA)

In order to solve the TSP, this study introduces the Ant Colony Algorithm (ACA). Ants are a kind of collective animal in nature, and they show strong sociality through overall cooperation. In the process of looking for food, they are able to always locate the route that takes them the shortest distance from the source of food to the ant colony nest [19-21]. In 1991, Marco Dorigo, a computer scientist at the Free University of Brussels, published the latest work on ACA in his doctoral dissertation. Later, he and his colleagues used the characteristics of ants to formally simulate the ant colony algorithm system on the software, that is, use the ACA to solve the TSP. The specific implementation steps of the ACA are presented in Fig. 4.

A probabilistic optimization technique called the Quantum Ant Colony Algorithm (QACA) is based on the idea of quantum computing. The foundation of QACA is the theory and idea of quantum computing. The quantum rotation gate updates the pheromone's quantum bits for encoding. Furthermore, the algorithmic properties are unaffected by changes in the population size. QACA is capable of both "exploration" and "mining," and its convergence speed is fairly quick. Additionally, it has a significant capacity for global optimization and a diverse population. In QACA, pheromones collected by ants on objects are encoded using quantum bits. The pheromone update that was acquired on the object that the ant is using is then converted by the quantum rotation gate into an update of the qubit probability amplitude. This update also causes the object's qubits to be updated.

Comparing the ACA and QACA, one draws a conclusion that the ACA is easy to combine with other algorithms, and has the characteristics of positive feedback, robustness, distributed computing, etc. However, it's easier for the ACA to fall into a local optimal solution. Even worse, the optimization rate for the ACA is low. Instead, The QACA is an innovative form of the optimization algorithm known as swarm intelligence. The algorithm not only continues the positive feedback of the ACA, is easy to distribute computing, and has high robustness, but also has efficient mechanisms such as the parallelism of quantum computing. Meanwhile, it has the advantages of a fast convergence rate, strong global optimization ability, etc. Hence, QACA can solve optimization problems efficiently.

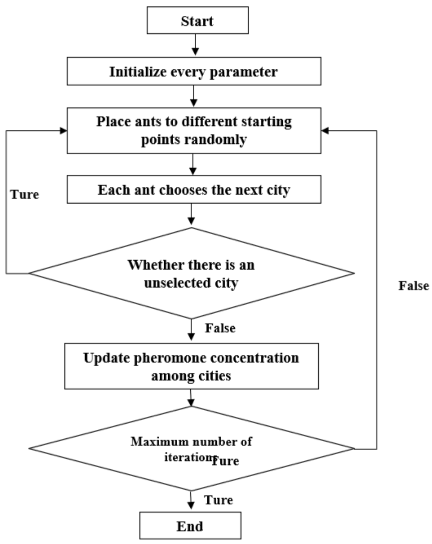

Fig. 4 Flow chart of ACA

5. Limitations and Future Outlooks

The research on quantum computing technology began in the 1980s, and the key technologies include the physical realization of quantum processors, quantum coding, quantum algorithms, quantum software, peripheral guarantees, and upper-layer applications. The physical realization of quantum processors is the main research hotspot and core bottleneck of quantum computing technology at this stage, including superconductivity, ion traps, photons, silicon quantum dots, topology, and other schemes. In terms of superconducting technology routes, Google has launched a 72-bit qubit processor. However, the currently reported processor structure design and qubit entanglement degree are not uniform, and most of them do not achieve global entanglement. Though the ion trap technology route has good coherence performance, a large number of entangled qubits, and high fidelity of logic gates, the manipulation speed is relatively slow. In addition, the technical means to realize topological qubits and operate topological qubits are still under study. Although quantum dots have good scalability, the coherence time of their qubits is short, and the number of qubits is in the single digits.

Quantum algorithms and software are the nerve centers for quantum processor hardware to give full play to computing power and solve practical problems. The acceleration capability of quantum computing compared to classical computing is closely related to quantum algorithms. The Shor's algorithm and Grover's algorithm have exponential and square root speedups in breaking passwords and searching data. However, the current core algorithms are still limited, and the existing algorithms only have theoretical advantages on specific problems. Quantum computing is not yet as universally applicable to solving various problems as classical computing.

In the future, quantum supremacy must be achieved first, so that quantum computing simulators have the computing power to surpass traditional supercomputers for specific problems. Secondly, through research, a dedicated quantum computing simulation system with application value can be realized, and play a huge role in combinatorial optimization, machine learning, quantum chemistry, etc. The third stage is to realize a programmable universal quantum computer, which will play an important role in classical password cracking, big data search, artificial intelligence, etc.

6. Conclusion

In summary, this study has made a comparison between the conventional algorithms and the quantum algorithms. Through the comparison between CGA and QGA, one can find that quantum algorithms are far superior to conventional algorithms in terms of computing volume, speed, global optimization ability, etc. Moreover, the QACA is based on quantum computing and combines the basic characteristics of the ACA. It not only continues the positive feedback, distributed computing and high robustness of the ant colony algorithm, but also gives play to many advantages of quantum computing. To sum up, compared with conventional algorithms, quantum algorithms are more powerful in solving specific problems. This work only selects two typical problems for comparison, which has certain limitations. In the future, more studies ought to devote me to the research of quantum computing applications, so as to provide some ideas for further research.

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