Research on Quantum Computing Standard System Architecture and Roadmap

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Abstract. Quantum computing is an important branch of quantum information technology. Quantum computing is far more powerful than traditional computing in solving some problems, and it has great potential for commercial and military applications. Firstly, this paper introduces the status quo of quantum computing research and the status of domestic and foreign standards, and then discusses the demands of quantum computing standards, and expounds on the necessity of a quantum computing standard system. Then give the quantum computing architecture standard system diagram. Finally, there is a roadmap for Quantum computing standardization is given, including the short, medium and long term. The architecture and the roadmap will be helpful to guide the standardization work as well as the application development.

1. Introduction

Quantum information technology is based on quantum mechanics, which obtains, transmits and processes information in a way that cannot be realized by classical theory through manual observation and regulation of microparticle systems such as photons and electrons and their quantum states, and by virtue of unique physical phenomena such as quantum superposition and quantum entanglement. Quantum information technology mainly includes three technical fields: quantum computing, quantum communication and quantum measurement [1]. Quantum computing, as an important exploration direction for the cross-domain development of computing power in the future, has a strong parallel computing potential far beyond classical computing in principle, and is expected to provide potential solutions to large-scale computing problems required by chemistry, biomedicine, smart grid, artificial intelligence, finance, cryptanalysis, weather forecasting, resource exploration, etc. In recent years, with the rapid development of scientific research on the prototype of quantum computing principles and experimental platforms, experimental verification of the advantages of quantum computing continues to achieve phased results [2]. The field of quantum computing is gradually forming an all-around development pattern integrating academic research, engineering research and development, application exploration and industrial construction.

As an emerging technology field, quantum computing is currently in the primary stage of technical research and industrial exploration. The technical direction has not been unified in the industry, and the standardization needs are not clear. The only approved international standard project is ISO/IEC 4879 <Information technology- Quantum computing terminology and vocabulary>, which lacks systematic standard construction.

With the continuous progress of quantum computing technologies, the continuous integration of academia and industry, the continuous exploration of new application models, and the continuous investment of commercial capital, in order to make use of the physical properties of quantum entanglement and superposition of quantum computing, we have developed technical potential in data

storage, characterization, and efficient parallel computing, making it a breakthrough application in various fields. The standardization of quantum computing has become an urgent issue for many Standardization Development Organizations.

2. Quantum Computing Research and Standardization Research Status Domestically and Abroad

2.1. Quantum Computing Research Status Domestically and Abroad

Although the quantum computing technology is still in the primary research stage, the quantum computing industry has a good momentum of development, and the ecology is growing. The key technologies include quantum chips, quantum basic software and quantum application software [3].

Quantum chip is one of the core components of quantum computer. At present, there are two main technical routes for its realization: electrical route and optical route. The electrical route, also known as the solid-state device route, is mostly used in the industry. Most mainstream enterprises carry out research in superconductivity and semiconductor; Optical routes mainly include ion trap and optical quantum, which are mostly used in scientific research; In addition, there are also a few enterprises focusing on topology, neutral atom and other technical routes. Figure 1 shows the main quantum chips technology route at present.

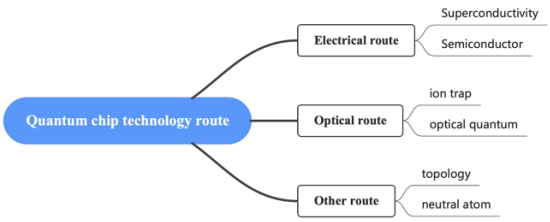

Figure 1. Quantum chip technology route.

In terms of the choice of technical route, Google, IBM and Rigetti have taken the superconducting technical route, and the representative achievement is the 72-bit quantum processor released by Google in 2018. Intel and OriginQ also focus on the superconducting route, and also work on the semiconductor direction. Honeywell and IonQ focus on the direction of ion trap, and the representative achievement is the 32-bit QV400 ion trap quantum computer released by IonQ in 2020. Microsoft focuses on the topology route and is still in the research stage. At present, superconductivity and ion trap routes are leading, and many technical routes have not converged, and none of them has fully realized the practical application of quantum computing. Google completed the prototype of quantum computing Sycamore through the superconducting route in 2019 and announced the realization of quantum superiority. One year later, the University of Science and Technology of China adopted the optical route to develop the quantum computing prototype "Jiuzhang" and realized quantum superiority, which is 10 billion times faster than the "Sycamore". In 2021, the Institute of Quantum Information and Quantum Technology Innovation of the Chinese Academy of Sciences successfully developed the 62-bit programmable superconducting quantum computing prototype "Zuchongzhi", and realized the programmable two-dimensional quantum walk on this basis.

Quantum basic software consists of quantum cloud platform, language processing system, quantum operating system and quantum algorithm. The representative enterprises of domestic quantum cloud platforms mainly include Alibaba, Huawei and OriginQ. The superconducting quantum computing cloud platform was independently developed by OriginQ [4].

Quantum computing has broad application prospects in quantum chemistry, quantum artificial intelligence, etc. Quantum chemistry is one of the most promising applications of quantum simulation.

In foreign countries, IBM launched the "IBM Q" project at the beginning of 2017. Google first realized the use of quantum computers to simulate chemical reactions in 2020, that is, the use of Sycamore processors to simulate the isomerization of diazene molecules composed of two nitrogen atoms and two hydrogen atoms [5]. Quantum artificial intelligence has certain development potential. Google, IBM, Baidu and other companies have stepped into this field. Quantum computing and artificial intelligence promote each other. However, due to the maturity of technology, such as the number of quantum bits is small, quantum error correction technology is not mature, and quantum machine learning lacks a perfect theoretical framework, there is still a certain distance from the real application of quantum computing to artificial intelligence. In the future, with the development of quantum hardware and the improvement of artificial intelligence technology, the cross combination of these two fields may lead to a breakthrough in real practical applications. The breakthrough directions may include processing huge amounts of data, building better models, researching more accurate algorithms, and using more data sets.

2.2. Quantum Computing Standardization Status Domestically and Abroad

Quantum computing standardization work has been launched since 2018 under ISO/IEC JTC 1, at present, international standards organizations such as IEC, ITU-T, regional standards organizations such as CEN, CENELEC, and several other industry focus SDOs such as IEEE, IETF, EU Qflag, NIST and other research institutions are actively carrying out the layout of quantum information standardization and the preliminary work of standardization research.

In 2018, ISO/IEC JTC 1 established Quantum Computing Research Group SG 2 to carry out research on quantum computing technology trends and complete the technical trend report; In 2019, ISO/IEC JTC 1 reconstituted the Quantum Computing Advisory Working Group AG 4 to continue to carry out the standardization research and demand analysis of quantum computing in the field of information technology. The group formally completed the research and sorting work and submitted the research report to JTC 1 at the beginning of 2020. At the same time, it was suggested that JTC 1 formally establish a corresponding technical organization to carry out the standardization demand research of information technology on quantum computing, and sort out application scenarios and cases, develop terminology standards. In April 2020, the international standard proposal of "Information Technology-Quantum computing terms and vocabulary", led by China, was successfully established in ISO/IEC JTC 1 to standardize common terms and vocabulary in the field of quantum computing. In June of the same year, based on the project establishment of this international standard, the ISO/IEC JTC 1/WG 14 Quantum Computing Working Group was formally established, with Chinese experts as the conveners. At present, there are 4 projects undergoing inside WG 14, shown in table 1. At the same time, WG 14 is also working on the roadmap research on Quantum Information Technology inside JTC 1, and it is hopefully that the first international standard will be published in 2023.

Table 1. ISO/ IEC JTC 1/WG 14 projects undergoing.

No.	**Project No. under ISO/IEC**	**Title**	**Type**	**Status**
1	ISO/IEC 4879	Information technology - Quantum computing - Terminology and vocabulary	IS	DIS
2	ISO/IEC TR 18157	Information technology – Introduction to quantum computing	TR	DTR
3	ISO/IEC PWI 18660	Information technology – Quantum machine learning datasets	PWI	-
4	ISO/IEC PWI 18670	Information technology – General requirements for quantum resource simulation platform	PWI	-

IEC issued the White Paper on Quantum Information Technology in 2021, analysing IEC's standardization needs for quantum information technology, and proposing short-term and long-term standardization directions from the aspects of technical organization and standard projects. The IEC SMB SEG 14 Quantum Technology was formally established in 2022, aiming to sort out the standardization direction of IEC from the perspective of system standardization and help IEC cooperate with other SDOs.

In ITU-T, FG-QIT4N Quantum Information and Network Technology Focus Group [6] is mainly responsible for the pre standardization of quantum computing. The group was officially established in September 2019, mainly to carry out standardized pre research on new services and applications driven by quantum enhanced network technology and quantum information technology. Quantum computing, quantum cloud computing, distributed quantum computing, blind quantum computing, quantum information network, quantum internet, etc., as important technical contents of FG-QIT4N focus group, carry out pre standardization among WG 1.

CEN/CENELEC formally established the JTC 22 on Quantum Technology in the middle of this year to carry out research on quantum technology standardization from the perspective of the European Union, formulate a roadmap for quantum technology standardization in the European Union, which is planned to be released in 2023, and carry out relevant standards promotion according to the roadmap research.

IEEE is carrying out two projects related to quantum computing, as shown in table 2, including quantum computer mechanism, quantum computing performance measurement and benchmark, quantum algorithm design and development experiment, etc. At the same time, IEEE is also developing quantum technology terminology. Quantum computing performance measurement and benchmark, which covers quantum computing performance measurement and is used to standardize the performance benchmark of quantum computing hardware and software.

Table 2. IEEE projects related with Quantum Computing.

No.	**Project No. under IEEE**	**Title**	**Status**
2	IEEE P2995	Quantum Algorithm Design and Development Experiment	Undergoing
3	IEEE P3120	Quantum computing architecture	Undergoing
4	IEEE P7131	Quantum computing performance measurement and performance benchmarking	Undergoing

The Internet Technology Research Task Force (IRTF) of the IETF Standards Organization has established the Quantum Internet Research Group (QIRG). The research group is committed to studying the architecture, enabling technology, routing protocols, key devices and other aspects of quantum information networks, and relying on the new generation of quantum interconnection networks, it carries out the standardization work of quantum computing, quantum sensing, quantum communication and other service applications. Quantum information processing, quantum information interconnection and networking protocols related to quantum computing are discussed in the QIRG group.

The National Institute of Standards and Technology (NIST) has launched the technology solicitation and evaluation standardization project of quantum public key cryptography algorithm in the case of quantum information confrontation. The goal of this project is to upgrade the existing public key cryptography system with Post Quantum Cryptography technology in the classical computing system and future quantum computing system, In the area of quantum computing, it provides network information security solutions. Compared with international organizations, China started a little later in the standardization of quantum information technology and is actively promoting layout related work. In August 2018, the Technical Committee for Standardization of Quantum Computing and Measurement

(TC578) was established, which is mainly responsible for the preparation and revision of national standards in the field of quantum computing and measurement [7]. At present, the first domestic standard on Quantum Computing is already in its approval process, which is also the terminology project. The National Standardization Administration Committee is responsible for business guidance. The Internet of Things Subcommittee of the National Information Technology Standardization Technical Committee (SAC/TC 28/SC 41, SC 41) also established an advanced computing research group, carry out sorting out of advanced computing technology system and research on standardization requirements, including standardization research in quantum computing.

3. Requirements Analysis of Quantum Computing Standards

From the perspective of the progress and layout of quantum computing standards at home and abroad, there is still a certain gap between China's quantum computing field and the advanced level in Europe and the United States in terms of computing hardware, software, theory, algorithms, infrastructure, testing instruments, etc. At present, both scientific research and industrial fields are in the initial stage, so the standardization process of quantum computing is also lagging. From the perspective of the key work direction of quantum computing standardization, as quantum computing technology has not yet converged, the business model has not yet been clarified, and the key technology products and marketization work are still developing, the current quantum computing standardization mainly focuses on the formulation of scientific terminology definitions and the analysis of potential application scenarios and needs of quantum computing:

- The standardization of the definition of quantum computing terms is conducive to the alignment of information technology between academia and industry, reaching a consensus on methodology, and contributing to the smooth development of quantum computing technology route and the smooth transformation of production, education and research achievements.
- On the other hand, the discovery and effectiveness analysis of potential application scenarios of quantum computing at the business level and network level will help to obtain the continuous attention of the demanders, researchers and capital investors, thus accelerating the accelerated development of quantum computing technology and industrialization process. In terms of standardization of key components, software, security, networking and evaluation, technical research and analysis and standardization pre research will continue to be the main work in the future. However, in general, the work layout and development direction of quantum computing standardization in China are consistent with the general trend of international standardization.

With the joint efforts of all parties involved in industry, university, research and application, it has good development potential in the future.

4. Quantum Computing Standard System Architecture

4.1. Architecture Design Principles

The design principles of the standard system mainly include inheritance, practicality and progressiveness. The first is inheritance. It is necessary to take the achievements that have been studied and tested in China as the basis for preparing the quantum computing standard system. In the construction of the quantum computing standard system, it is necessary to selectively inherit and incorporate the widely applicable contents into the standard system. The second is to consider practicality. The standard system of quantum computing comes from the practical needs of the industry, and its formulation process closely revolves around the national guidelines and objectives for the development of quantum computing. The standard system should be able to guide the R&D, production and other activities of relevant participants in the field of quantum computing and support the development of the industry. There should also be progressiveness， in view of the potential subversive impact of quantum computing technology, the systematic deployment of quantum computing standard

system has a very important guiding value for China to carry out the promotion of relevant standard plans and international standardization.

4.2. Architecture Diagram

The framework of quantum computing standard system is designed according to three branches: basic standards, technical standards and application standards. On this basis, the third level standardization direction is given based on analysis, as shown in figure 2.

- Basic standards include terminology, architecture, test benchmark, ethical regulations, etc
- Technology standards include components, quantum computers, quantum algorithms, interfaces, interoperability, etc
- Application standards include applications of quantum computing in artificial intelligence, quantum chemistry, quantum finance, intelligent transportation, etc., reflecting the technical and application advantages of quantum computing in optimization and simulation.

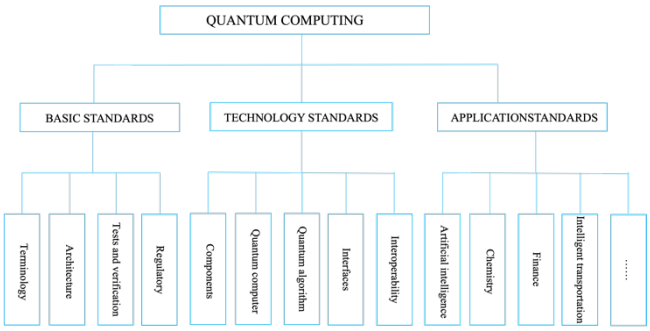

Figure 2. Quantum computing standard system diagram.

5. Quantum Computing Standardization Roadmap

In order to steadily promote the work of quantum computing standards, based on the technology development trend and the results discussed by the ISO/IEC JTC 1/WG 14 Quantum Computing and the domestic technical counterpart expert group, the circuit diagram mainly gives the development route of the basis, key technologies, applications, etc. involved in quantum computing, which is described in three stages: the near-term (before 2025), the medium- and long-term (2025-2030), and the long term (2030-2025). The standard roadmap is shown in figure 3.

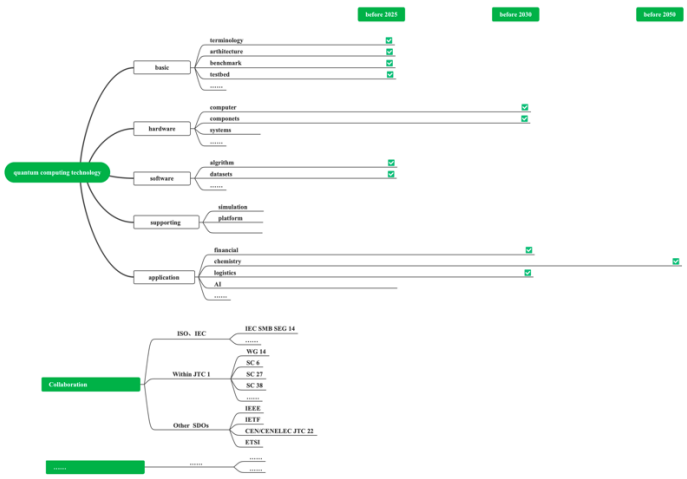

Figure 3. Quantum computing standardization roadmap.

The near-term plan is to first complete the standard development of basic terms, architecture, benchmarks, test beds and use cases; The medium-term plan mainly completes the hardware part, including the development of standards for quantum computers, components and systems, and the algorithm level standards for software. Specific quantum basic algorithms (such as Shors algorithm, Grover algorithm, QFT algorithm, etc.) are used to test the performance of quantum computers in practical related tasks; The long-term planning should complete the standards for quantum AI, quantum finance, quantum chemistry, quantum computing for smart grid and logistics and other application fields, with the purpose of evaluating the ability of quantum computers to solve specific problems (such as large number decomposition, combinatorial optimization, machine learning, simulation).

6. Conclusions

Based on the analysis of the category of quantum computing, the development status and trend of quantum computing technology and standards, and following the principles of inheritance, practicality and progressiveness, this paper presents the framework of quantum computing standards and the roadmap of quantum computing standards. It is a directional guidance for the follow-up standardization work at home and abroad.

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