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Quantum Software Ecosystem: Stakeholders, Interactions and Challenges

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Abstract. The emergence of quantum computing proposes a revolutionary paradigm that can radically transform numerous scientific and industrial application domains. The ability of quantum computers to scale computations imply better performance and efficiency for certain algorithmic tasks than current computers provide. However, to gain benefit from such improvement, quantum computers must be integrated with existing software systems, a process that is not straightforward. In this paper, we investigate the quantum computing ecosystem and the stakeholders involved in building larger hybrid classical-quantum systems. In addition, we discuss the challenges that are emerging at the horizon as the field of quantum computing becomes more mature.

Keywords: Quantum software · Quantum ecosystem · Value chain

1 Introduction

Quantum computing holds great promise as a revolutionary technology that has the potential to transform various fields. By harnessing the principles of quantum mechanics, quantum computers can perform complex calculations and solve problems that are currently intractable for classical computers. This promises breakthroughs in areas such as cryptography, optimization, drug discovery, materials science, and machine learning. Quantum computing's ability to leverage quantum mechanics properties like superposition, interference and entanglement can unlock significant speedups and enable more accurate simulations of quantum systems.

The development of quantum software faces numerous challenges that need to be addressed for harnessing the power of quantum computing effectively. Firstly, the limited availability and instability of quantum hardware pose significant obstacles. Quantum computers are prone to errors and noise, necessitating the development of robust error correction techniques. Further, quantum programming languages and tools are still in their nascent stages, requiring improvements to facilitate efficient software development. More, the scarcity of skilled quantum

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software developers and a lack of standardization hinder the widespread adoption of quantum software. As quantum systems scale, the complexity of designing and optimizing quantum algorithms increases, demanding novel approaches to algorithm design and optimization. Addressing these challenges is crucial for realizing the full potential of quantum computing and enabling the development of practical quantum software applications.

In this paper, we delve into the realm of the quantum software ecosystem and examine the interconnections among its stakeholders. Our focus centers on the intricate interplay between these entities, and we pinpoint their areas of influence within the technology stack. Ultimately, our objective is to provide both established stakeholders and emerging participants with insights that can inform their strategic decision-making.

The rest of the paper is structured as follows. The background is provided in Sect. 2. The ecosystem overview is presented in Sect. 3. The discussion of the value stream within the ecosystem is provided in Sect. 4. Concluding remarks are provided in Sect. 5.

2 Background

2.1 Qubit Implementation

The current candidates for building general-purpose quantum computers, as listed in Table 1, fall under the category of Noisy Intermediate-Scale Quantum (NISQ) systems. Although these quantum computers are not yet advanced enough to achieve fault-tolerance or reach the scale required for quantum supremacy, they provide an experimentation platform to develop new generations of hardware and quantum algorithms and validate quantum technology in real world use cases. Whether a quantum computer is general-purpose or specialized, the selection of quantum qubit implementation technology can significantly enhance hardware efficiency for specific problem classes. To make effective use of the hardware, application developers must consider these differences when designing and optimizing the software's functionality and operations.

2.2 Quantum Algorithms

Quantum algorithms are computational techniques specifically designed to harness the unique properties of quantum systems [2]. They offer significant advantages over classical algorithms in certain computational tasks. One key advantage is the ability to solve complex problems faster. For example, Shor's algorithm enables efficient factoring of large numbers, posing a potential threat to current encryption methods. Also, Grover's algorithm provides substantial speedup in searching large databases. Moreover, quantum algorithms can address optimization problems more effectively, leading to improved solutions in areas like portfolio optimization, logistics, and drug discovery, to name some concrete examples.

Table 1. Qubit implementation technologies.

Qubit Technology	Description	Applicability
Superconducting	Tiny superconducting materials are cooled to extremely low temperatures to manifest their quantum properties	General-purpose quantum computing, suitable for various types of problems
Trapped Ion	Ions are trapped within electromagnetic fields	General-purpose quantum computing, with potential for high coherence and low error rates
Photonic	Quantum information stored in photons can be manipulated and transmitted over long distances	General-purpose quantum computing, suitable for communication and cryptography applications
Annealing	Special purpose quantum computers designed to solve optimization problems	Specialized quantum computing, targeted at optimization and sampling problems
Topological	A new approach to quantum computing that leverages the properties of topological states of matter to create qubits. Topological qubits are based on collective properties of an ensemble of particles	General-purpose quantum computing, aimed at achieving fault-tolerant operations

2.3 Software

A typical quantum program performs a specialized task as part of a larger classical program. The quantum program is submitted as a batch task to a classical computer that controls the operation of the quantum computer. The classical computer schedules the task execution and provides the result to the classical program when the job completes. To support this process, numerous alternatives for tooling exist.

An application developer use tools like Qiskit[1] and Cirq[2] for writing, manipulating and optimizing quantum circuits. These Python libraries allow researchers and application developers to interact with nowadays' NISQ computers, allowing them to run quantum programs on a variety of simulators and hardware designs, abstracting away the complexities of low-level operations and allowing researchers and developers to focus on algorithm design and optimization.

Tools like TensorFlow Quantum[3] and PennyLane[4] play a crucial role in facilitating the development of machine learning quantum software. These frameworks provide the high-level abstractions and interfaces that bridge the gap between quantum computing and classical machine learning. They allow researchers and developers to integrate quantum algorithms seamlessly into machine learning development process by providing access to quantum simulators and hardware,

[1] https://qiskit.org.
[2] https://quantumai.google/cirq.
[3] https://www.tensorflow.org/quantum.
[4] https://pennylane.ai.

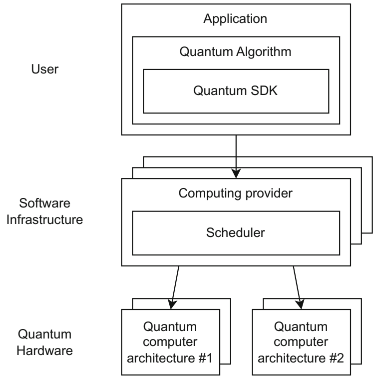

Fig. 1. Quantum stack layers and components.

as well as offering a range of quantum-friendly classical optimization techniques. TensorFlow Quantum leverages the power of Google's TensorFlow ecosystem, enabling the combination of classical and quantum neural networks for hybrid quantum-classical machine learning models. PennyLane offers a unified framework for developing quantum machine learning algorithms, supporting various quantum devices and seamlessly integrating them with classical machine learning libraries.

Traditional cloud computing providers, such as AWS Bracket[5], Azure Quantum[6], Google Quantum AI[7] or IBM Quantum[8], offer comprehensive quantum development services. These services are designed to optimize the development process, with integrated tools like Jupyter[9] notebooks and task schedulers. Developers can create quantum applications and algorithms across multiple hardware platforms simultaneously. This approach ensures flexibility, allowing fine-tune algorithms for specific systems while maintaining the ability to develop applications that are compatible with various quantum hardware platforms.

3 Ecosystem Layers and Stakeholders

The quantum ecosystem can be segmented into distinct functional layers, as illustrated in Fig. 1. The first one is the *user* layer, encompassing applications and supplementary software components crafted by third-party developers. This includes quantum algorithms and software development kits (SDKs) for quantum circuits, such as Cirq and Qiskit. The *infrastructure* layer, in contrast, comprises the software employed by computing providers to manage and execute quantum

[5] https://aws.amazon.com/braket/.
[6] https://learn.microsoft.com/en-us/azure/quantum/.
[7] https://quantumai.google.
[8] https://quantum-computing.ibm.com.
[9] https://jupyter.org.

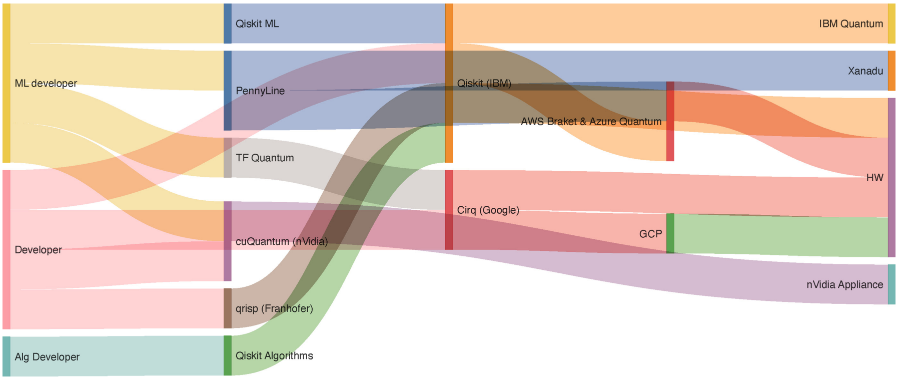

Fig. 2. Quantum ecosystem: stakeholders, software tools and interactions

computing tasks specified within the user layer. Finally, the *hardware* layer pertains to the physical hardware and accompanying control software essential for implementing the qubits required to execute quantum circuits.

From a stakeholder perspective, each functional layer is characterised by specific entities of interest. The user layer is primarily populated by the business and scientific stakeholders that commission the development of the respective applications. Typically, the these applications use third-party algorithm libraries and quantum circuit SDKs. Quantum algorithm developers and researchers often contribute to these libraries as a means to disseminate their work. Similarly, the quantum circuit SDKs provide unique idioms to program quantum circuits making easy for developers to define and control the individual quantum gates. At the infrastructure layer, we find the major cloud computing providers and to a lesser extend the quantum hardware manufacturers. The hardware layer consists of the quantum computer manufacturers and the myriad of suppliers that provide the components for the respective hardware.

4 Discussion

Today, Cirq and Qiskit have established market dominance in the general purpose quantum computing. Similarly, PennyLane is the dominant ML specialized framework, besides Cirq and Qiskit. These frameworks provide strong control points for Google, IBM, and Xanadu, respectively, to control the programming space, see Fig. 2. Independent hardware manufacturers have to provide back-end implementations for these SDKs in order to enable application developers to write programs that use their devices. Similarly, frameworks like qrisp [3], which provides an alternative quantum circuit programming model, have to fold into the realities of the ecosystem and provide Qiskit-compatible back-end wrappers to be able to execute on existing quantum hardware.

As the race towards quantum supremacy is still in its infancy, the quantum hardware needs to evolve from the current computers that offer tens of qubits to at least hundreds and being able to execute circuits with thousands of gates [1]. As the hardware development is resource intensive, the manufacturers might find themselves isolated into the lower layer of the stack, limited to providers of back-end implementations for the established programming frameworks. However, to be able to interact with developers they have to expose additional functionality at the appropriate layer in the upper software stack, above Qiskit or PennyLane for example.

The quantum computing community, deeply rooted in scientific principles, embraces collaboration and often adopts an open-source approach for many frameworks and software tools. Nevertheless, these projects are controlled by commercial interests, and open governance is often lacking or limited. A notable exception is QIR Alliance[10], a Linux Foundation led effort aiming to develop standards for interoperability in the quantum compiler space. An area of special interest is tooling related to scheduling and execution, where the cloud providers have a clear advantage. An open source execution environment developed using an open governance model, similar to Kubernetes, would allow smaller players to operate quantum computing services in a cost efficient matter.

5 Conclusions

The emergence of quantum computing is spurring a new ecosystem, where quantum computers must be integrated with existing software systems and their development. In this paper, building on early research results and practical observations, we have mapped out the stakeholders and shed light on the dynamics within today's quantum software ecosystem. However, more in-depth investigation is needed for the exploration of stakeholders' unique interests and fundamental characteristics of the systems they provide and propose. To this end, our analysis of the quantum ecosystem, its stakeholders, and their interactions serves as a valuable starting point, setting the stage for deeper exploration and enhanced understanding of the quantum computing field.

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