An Overview of the Cloud Quantum Computing Market (September 2022)

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***Abstract*—The market for cloud quantum computing is growing. This is happening with cloud service providers, quantum computing hardware providers, and quantum computing software solutions. This paper provides an overview of what researchers and businesses will find available to explore the quantum computing space.**

Keywords—market, cloud, quantum, hardware, software

I. Introduction

The market for quantum computing solutions is expanding. From the major cloud computing providers to large-cap technological corporations to small startups, investments in quantum computing are growing [1], as is the number of patents around the technology [2]. Amazon, Microsoft, Google, and IBM have all introduced varying cloud service offerings targeted toward research and industry applications of the latest quantum computing hardware. In many cases, these offerings leverage the capabilities of startups that host quantum computing hardware. Along with the rush to provide access to the hardware, software solutions are being introduced and refined to offer a many-pronged approach to tackling the challenges of the noisy intermediate-scale quantum (NISQ) hardware. This paper aims to provide a summary overview of the state of cloud quantum computing, comparing and contrasting what is currently available to the average researcher or business.

II. Cloud Service Providers

A. Amazon Web Services (AWS)

AWS holds roughly 33% of the overall cloud market [3], [4], and it has approached quantum computing similarly to how it has approached the rest of its business model. Much like infrastructure-as-a-service (IaaS), software-as-a-service (SaaS), and platform-as-a-service (PaaS), AWS looks to offer quantum-computing-as-a-service (QCaaS). Rather than focusing directly on producing quantum computing hardware, AWS puts customers in touch with multiple providers [5]. In doing so, AWS provides access to several different types of quantum hardware, superconducting, trapped ion, photonic, and quantum annealing among them.

B. Microsoft Azure

Azure has seen consistent growth in recent years, and it currently sits in the number two spot in the cloud market with 22% [3], [4]. Like AWS, it has also chosen to offer a breadth of providers and services to cover the quantum computing space [6]. As a differentiator, Azure offers a few software solutions that are best described as quantum-inspired. These algorithms have been developed with insights gleaned from research into quantum computing, but they are run on classical computing hardware [7]. In addition, Microsoft is actively researching building topological qubits to build its quantum computing hardware [8]. These topological qubits are thought to offer a more fault-tolerant approach to building quantum gates [9].

C. Google Cloud Platform (GCP)

GCP trails AWS and Azure, holding third in the cloud market with approximately 10% market share [3], [4]. GCP appears to lag behind its top two competitors regarding cloud quantum computing services. While Google is actively involved in developing its quantum computing hardware, access to that hardware via its Quantum AI service is only available to approved projects [10]. For those looking for a more on-demand experience, GCP does have a partnership with IonQ [11], but it currently lacks the variety of options available with AWS and Azure. Google received much publicity over its claim of achieving quantum supremacy in the latter half of 2019 [12]. Quantum supremacy is meant to demonstrate the usage of a quantum computer to solve a problem that would be practically impossible for classical computing hardware. Within a few weeks, IBM rejected Google's claim, showing it could solve the same problem in a reasonable amount of time and with greater accuracy using its Summit supercomputer [13], [14].

D. International Business Machines (IBM)

IBM sits well below the likes of AWS, Azure, and GCP in cloud market share, holding 4% as of June 2022 [15]. However, IBM has the potential to be very appealing to the quantum computing market. Running its own hardware, IBM offers access to systems from five qubits up to 127 qubits [16]. IBM is aggressively positioning itself to be a leader in the quantum hardware space, announcing public roadmaps with qubit counts as targets. IBM expects to unveil a 433-qubit processor, IBM Osprey, later this year, and it is developing a processor with over 1,000 qubits, IBM Condor, that it intends to introduce in 2023 [17]. Whether it will continue to hit these lofty targets as it has previous ones remains to be seen.

E. Other Cloud Providers

The rest of the cloud market is somewhat fractured [3], [4], and most of the providers do not have their own quantum computing offerings just yet. As a couple of examples, the

Alibaba DAMO Academy (Academy for Discovery, Adventure, Momentum, and Outlook) is working on software, research, and collaboration for now [18], and Red Hat OpenShift is focusing on allowing developers an easier startup to work with quantum computing, connecting to IBM Quantum on the backend [19], [20]. However, these efforts are largely still in their infancy, and customers should weigh the pros and cons of pursuing them over the market leaders.

III. Quantum Computing Hardware Providers

In searching for the best quantum computer, many companies are vying for funding [1]. Each company has a different philosophy on what underlying hardware approach or fabrication technique will result in the optimal solution. For some, a universal quantum computer capable of running any algorithm is the goal, and for others, the belief is that the quantum computer should be specialized to solve practical problems. The startup space has several interesting companies innovating in the quantum computing industry.

A. *IonQ*

IonQ, Inc. is a United States quantum computing company headquartered in College Park, Maryland, and founded in 2015 [21]. Pursuing cross-market relationships with AWS, Azure, and GCP [5], [6], [11], IonQ offers a trapped ion quantum computing solution. Trapped ion quantum computers offer one approach to universal quantum computation [22]. IonQ's solution relies upon a silvery, rare-earth atom called ytterbium. By using a laser to remove an electron from a ytterbium atom (Yb), a ytterbium ion (Yb+) is produced. IonQ then uses rapidly oscillating voltages to trap the ion in 3d space [23]. IonQ has shown this configuration offers both long-lasting coherence times and high fidelity control over individual gates, allowing them to perform individual qubit addressing [24]. IonQ had a 2020 valuation of $240MM, having raised three rounds of funding amounting to $82MM for the company [25].

B. *D-Wave*

D-Wave Systems Inc. is a Canadian quantum computing company headquartered in Burnaby, British Columbia, and founded in 1999 [26], [27]. D-Wave focuses on providing "the fastest path to practical, real-world applications with customer value [27]." D-Wave offers quantum annealing solutions, an approach that specializes in complex optimization problems where the solution is the best of many possible options [28]. D-Wave refers to its underlying hardware as quantum processing units (QPUs) which are formed of lattices of interconnected qubits joined together by couplers [29]. Many different business problems can be reformulated as optimization problems. D-Wave's success stories include case studies concerning improving financial portfolios, determining optimal protein configurations to battle COVID-19, and bettering waste collection processes to reduce CO2 emissions [30]–[32]. D-Wave had a 2020 valuation of $170MM, having sixteen rounds of funding amounting to $241.11MM [26].

C. *Xanadu*

Xanadu Quantum Technologies Inc. is another Canadian quantum computing company. It is headquartered in Toronto, Canada, and it was founded in 2016 [33], [34]. Xanadu was the first company to market a photonics-based quantum computing platform, using light rather than electrons [35]. Xanadu has demonstrated usage of Gaussian Boson sampling, a classically hard-to-solve problem [36], using its Borealis photonic processor. Xanadu estimates it would take more than 9,000 years to achieve similar results with classical computing methods and views this as representing quantum computational advantage [37]. Xanadu has gone through four funding rounds and raised $135.58MM as of May of 2021 [34].

D. *Rigetti*

Rigetti & Co., Inc. is a United States quantum computing company. It is a publicly-traded company listed on the NASDAQ under the symbol RGTI [38]. The company headquarters is in California, and it was founded in 2013 [39]. Rigetti produces quantum computers and chips based on superconducting microwave devices. It utilizes a combination of modern silicon semiconductor processes as well as its own manufacturing methods to produce qubits and device layers. This process uses many materials including aluminum, indium, and niobium in order to construct the chip-based quantum processors [40]. Rigetti has partnerships with both AWS and Azure by way of its Quantum Cloud Services (QCS) platform [5], [6]. Rigetti had a 2020 valuation of $600MM, having six rounds of funding amounting to $197.70MM [39].

E. *Oxford Quantum Circuits (OQC)*

Oxford Quantum Circuits (OQC) is a United Kingdom quantum computing company that is headquartered in the town of Reading [41]. The company was founded in 2017, and it had the UK's largest-ever Series A round for a quantum computing company, pulling in £38MM [42]. OQC uses a patented three-dimensional architecture of superconducting circuits that it calls Coaxmon. It believes this approach provides a more flexible and scalable system by taking certain key components off-chip to simplify the process of wiring and connecting multiple qubits together [43], [44]. OQC is the first European quantum company available on AWS [5], [45].

The list of quantum computing hardware companies continues to grow, with the above being a small sample of a few of the more prominent names that are actively working with cloud service providers.

IV. Quantum Computing Software

As with the hardware side of quantum computing, the software for building quantum computing circuits and programming quantum computing algorithms continues to evolve. In addition to software designed with interoperability in mind—able to run on many different types of quantum computing hardware—some providers offer deep integration with their cloud services and hardware offerings by way of a software development kit (SDK). Several of these software solutions are based on the Python programming language, but there are also implementations modeled after other programming languages like C++, C#, and JavaScript.

A. AWS Braket Software Development Kit (SDK)

AWS provides an SDK to interact with its Braket cloud service [46]. Based on Python, the SDK uses a generic Device class to provide access to quantum processing units (QPUs) from D-Wave, IonQ, Oxford Quantum Circuits (OQC), Rigetti, and Xanadu [47]. AWS Braket also provides three different types of simulators. The state vector simulator (SV1) can simulate up to 34 qubits, and it is intended for circuits with all-to-all gates. The density matrix simulator (DM1) can simulate up to 17 qubits, and it is ideal for noise simulations or those focusing on error correction. The tensor network simulator (TN1) can simulate up to 50 qubits, and it uses a structured graph to find solutions for relatively large and complex quantum circuits [47]. This combination of simulators and actual hardware providers gives customers a wide variety of options to choose from when testing their circuit designs and quantum algorithms. The SDK also includes an implementation of the most common quantum gates, available through a generic Circuit class [48]. Alternatively, customers may submit instructions to AWS Braket hardware using the Open Quantum Assembly Language (OpenQASM), allowing for a lower-level and more imperative approach to circuit design [49], [50]. As OpenQASM is an open-source framework, this approach might be worth considering if portability or vendor lock-in are concerns.

B. Microsoft Quantum Developer Kit (QDK)

Microsoft Azure offers what it calls the Quantum Development Kit (QDK), an SDK that is solely focused on building programs to run on either quantum hardware or quantum-inspired solvers [51]. Microsoft's open-source programming language for quantum computing is Q#, but the QDK also supports the Qiskit and Cirq programming languages. Q# differs from other quantum programming languages in that it offers a high-level abstraction that has no concept of quantum state or quantum circuits. The language offers support for quantum expressions and algorithms instead, with libraries offering support for domain-specific functionality in quantum chemistry, machine learning, and numerics [52]. In providing these resources, Q# offers an avenue for experimentation that may be more approachable to certain customers than beginning with quantum circuit design, and similar to C#, the language is strongly-typed, offering some protections against typing mistakes.

C. Google CIRQ

Google's Quantum AI is responsible for the development of Cirq, a Python software library that is an open-source framework for programming quantum computers [53], [54]. Cirq had its initial alpha release in 2018 [54], and even in alpha status, it was favorably compared to the existing offerings of Q#, Qiskit, and others [55]. Google has continued to refine the framework, adding Stim, a fast stabilizer circuit simulator, allowing for deeper research into error-correcting techniques [56]. With Microsoft's Azure Quantum and QDK incorporating support for both Qisket and Cirq [57], the library will continue to see further adoption and improvements.

D. IBM Qisket

IBM is the driving force behind Qiskit, another Python framework for quantum computing [58]. Similar to Microsoft's approach with Q#, IBM has developed modules for Qiskit that provide domain-specific functionality in the areas of machine learning, nature, finance, and optimization [58], [59]. However, Qiskit is also capable of defining quantum programs at the low level of circuits, allowing it to span a wide range of use cases. IBM is also focused on the Qiskit Runtime, optimizing the deployment of quantum applications via containers, as well as adding pay-as-you-go pricing to provide more flexibility for customers [60].

E. Other Quantum Computing Software Solutions

The list of quantum computing software tooling doesn't end with what is offered by the dominant cloud service providers. Several of the smaller quantum computing hardware providers have also published libraries or frameworks that are specialized to work with their implementations. D-Wave provides its Ocean SDK as a way of interacting with its quantum annealing solutions [61], and Rigetti offers Forest SDK [62], for example. Quantum++, an independent project, aims to deliver a highly portable and performant quantum computing library based on C++ [63], [64]. Quantum JavaScript (Q.js), another independent project, brings experimenting with quantum computing circuits to the web browser, allowing for rapid prototyping and experimentation with little upfront investment [65].

V. Conclusion

The many cloud service providers and quantum computing hardware providers continue to grow their offerings year after year. While quantum computing hardware providers focus on offering larger numbers of connected qubits in ever more stable configurations, cloud service providers look to connect customers with more options for their research and applications. While the overall quantum computing market is competing for investments and funding, there is also a tremendous amount of collaboration happening across the software space, with several companies trending toward open-source solutions and opening their services to the libraries and frameworks pioneered by others.

References

[1] E. Gibney, "Quantum gold rush: the private funding pouring into quantum start-ups," *Nature*, vol. 574, no. 7776, pp. 22–24, Oct. 2019, doi: 10.1038/d41586-019-02935-4.

[2] M. Aboy, T. Minssen, and M. Kop, "Mapping the Patent Landscape of Quantum Technologies: Patenting Trends, Innovation and Policy

Implications,” *IIC*, vol. 53, no. 6, pp. 853–882, Jul. 2022, doi: 10.1007/s40319-022-01209-3.

[3] “Huge Cloud Market Still Growing at 34% Per Year; Amazon, Microsoft & Google Now Account for 65% of the Total | Synergy Research Group.” https://www.srgresearch.com/articles/huge-cloud-market-is-still-growing-at-34-per-year-amazon-microsoft-and-google-now-account-for-65-of-all-cloud-revenues (accessed Sep. 22, 2022).

[4] “Q2 Cloud Market Grows by 29% Despite Strong Currency Headwinds; Amazon Increases its Share | Synergy Research Group.” https://www.srgresearch.com/articles/q2-cloud-market-grows-by-29-despite-strong-currency-headwinds-amazon-increases-its-share (accessed Sep. 25, 2022).

[5] “Amazon Braket Quantum Computers - Amazon Web Services,” *Amazon Web Services, Inc.* https://aws.amazon.com/braket/quantum-computers/ (accessed Sep. 20, 2022).

[6] “Azure Quantum - Quantum Cloud Computing Service | Microsoft Azure.” https://azure.microsoft.com/en-us/products/quantum/ (accessed Sep. 20, 2022).

[7] A. Ramanan, “Toshiba launches new SQBM+ quantum-inspired optimization provider on Azure Quantum,” *Microsoft Azure Quantum Blog*, Jun. 27, 2022. https://cloudblogs.microsoft.com/quantum/2022/06/27/toshiba-launches-new-sqbm-quantum-inspired-optimization-provider-on-azure-quantum/ (accessed Sep. 25, 2022).

[8] B. Potts, “Microsoft has demonstrated the underlying physics required to create a new kind of qubit,” *Microsoft Research*, Mar. 14, 2022. https://www.microsoft.com/en-us/research/blog/microsoft-has-demonstrated-the-underlying-physics-required-to-create-a-new-kind-of-qubit/ (accessed Sep. 25, 2022).

[9] R. Raussendorf, J. Harrington, and K. Goyal, “Topological fault-tolerance in cluster state quantum computation,” *New J. Phys.*, vol. 9, no. 6, pp. 199–199, Jun. 2007, doi: 10.1088/1367-2630/9/6/199.

[10] “Quantum Computing Service | Google Quantum AI.” https://quantumai.google/quantum-computing-service (accessed Sep. 25, 2022).

[11] K. Kissell and N. DeSantis, “IonQ quantum computer available through Google Cloud,” *Google Cloud Blog*. https://cloud.google.com/blog/products/compute/ionq-quantum-computer-available-through-google-cloud/ (accessed Sep. 25, 2022).

[12] E. Gibney, “Hello quantum world! Google publishes landmark quantum supremacy claim,” *Nature*, vol. 574, no. 7779, pp. 461–462, Oct. 2019, doi: 10.1038/d41586-019-03213-z.

[13] “IBM casts doubt on Google’s claims of quantum supremacy.” https://www.science.org/content/article/ibm-casts-doubt-googles-claims-quantum-supremacy (accessed Sep. 25, 2022).

[14] E. Pednault, J. Gunnels, D. Maslov, and J. Gambetta, “On ‘Quantum Supremacy,’” *IBM Research Blog*, Oct. 22, 2019. https://www.ibm.com/blogs/research/2019/10/on-quantum-supremacy/ (accessed Sep. 25, 2022).

[15] “Cloud Market Share 2022: An Overview of this Growing Ecosphere,” Sep. 19, 2022. https://www.wpoven.com/blog/cloud-market-share/ (accessed Sep. 25, 2022).

[16] “IBM Quantum Compute Resources,” *IBM Quantum*. https://quantum-computing.ibm.com/services/resources (accessed Sep. 22, 2022).

[17] J. Gambetta, “IBM Quantum roadmap to build quantum-centric supercomputers,” *IBM Research Blog*, Feb. 09, 2021. https://research.ibm.com/blog/ibm-quantum-roadmap-2025 (accessed Sep. 25, 2022).

[18] “Quantum Laboratory - DAMO Academy.” https://damo.alibaba.com/labs/quantum (accessed Sep. 25, 2022).

[19] P. Singh, “Quantum on OpenShift - part one, an introduction to quantum computing,” *Red Hat Emerging Technologies*, Sep. 30, 2020. https://next.redhat.com/2020/09/30/quantum-on-openshift-part-one-an-introduction-to-quantum-computing/ (accessed Sep. 25, 2022).

[20] O. Silkin and P. Singh, “Developing Circuits Using the Qiskit Operator: Quantum on OpenShift, Part Two,” *Red Hat Emerging Technologies*, Jun. 03, 2022. https://next.redhat.com/2022/06/03/developing-circuits-using-the-qiskit-operator-quantum-on-openshift-part-two/ (accessed Sep. 25, 2022).

[21] “About IonQ,” *IonQ*. https://ionq.com/company (accessed Sep. 25, 2022).

[22] A. M. Childs and I. L. Chuang, “Universal quantum computation with two-level trapped ions,” *Phys. Rev. A*, vol. 63, no. 1, p. 012306, Dec. 2000, doi: 10.1103/PhysRevA.63.012306.

[23] “IonQ | Our Trapped Ion Technology,” *IonQ*. https://ionq.com/technology (accessed Sep. 25, 2022).

[24] Y. Wang *et al.*, “High-fidelity Two-qubit Gates Using a MEMS-based Beam Steering System for Individual Qubit Addressing,” *Phys. Rev. Lett.*, vol. 125, no. 15, p. 150505, Oct. 2020, doi: 10.1103/PhysRevLett.125.150505.

[25] “IonQ, Inc. Company Profile: Financials, Valuation, and Growth,” *PrivCo*. https://system-privco-com.proxy.library.vanderbilt.edu/company/ionq (accessed Sep. 22, 2022).

[26] “D-Wave Systems Inc. Company Profile: Financials, Valuation, and Growth,” *PrivCo*. https://system-privco-com.proxy.library.vanderbilt.edu/company/d-wave-intl (accessed Sep. 25, 2022).

[27] “About D-Wave: The Practical Quantum Computing Company.” https://www.dwavesys.com/company/about-d-wave/ (accessed Sep. 25, 2022).

[28] “What is Quantum Annealing? — D-Wave System Documentation documentation.” https://docs.dwavesys.com/docs/latest/c_gs_2.html (accessed Sep. 25, 2022).

[29] “D-Wave QPU Architecture: Topologies — D-Wave System Documentation documentation.” https://docs.dwavesys.com/docs/latest/c_gs_4.html (accessed Sep. 25, 2022).

[30] “Multiverse Computing: Optimizing Financial Porfolios with Quantum Computing.” Accessed: Sep. 25, 2022. [Online]. Available: https://www.dwavesys.com/media/5qahck2o/multiverse_case_study_v8.pdf

[31] “Menten AI Battles COVID-19 with Quantum Peptide Therapeutics.” Accessed: Sep. 25, 2022. [Online]. Available: https://www.dwavesys.com/media/kjof1cdh/dwave_menten-ai_case_story-2_v4.pdf

[32] “Groovenauts and Mitsubishi Estate: Creating Sustainable Cities through Waste Collection Optimization.” Accessed: Sep. 25, 2022. [Online]. Available: https://www.dwavesys.com/media/bq5kh520/dwave_groovenauts_case_study_v3.pdf

[33] “About Xanadu,” *Xanadu*. https://www.xanadu.ai/about (accessed Sep. 25, 2022).

[34] “Xanadu Quantum Technologies Inc. Company Profile: Financials, Valuation, and Growth,” *PrivCo*. https://system-privco-com.proxy.library.vanderbilt.edu/company/xanadu-quantum-technologies (accessed Sep. 25, 2022).

[35] C. Middleton, “Quantum computing in the cloud - Xanadu discovered in Toronto,” Sep. 07, 2020. https://diginomica.com/quantum-computing-cloud-xanadu-discovered-toronto (accessed Sep. 25, 2022).

[36] C. S. Hamilton, R. Kruse, L. Sansoni, S. Barkhofen, C. Silberhorn, and I. Jex, “Gaussian Boson Sampling,” *Phys. Rev. Lett.*, vol. 119, no. 17, p. 170501, Oct. 2017, doi: 10.1103/PhysRevLett.119.170501.

[37] L. S. Madsen *et al.*, “Quantum computational advantage with a programmable photonic processor,” *Nature*, vol. 606, no. 7912, Art. no. 7912, Jun. 2022, doi: 10.1038/s41586-022-04725-x.

[38] “RGTI.” https://www.nasdaq.com/market-activity/stocks/rgti (accessed Sep. 25, 2022).

[39] “Rigetti & Co., Inc. Company Profile: Financials, Valuation, and Growth,” *PrivCo*. https://system-privco-com.proxy.library.vanderbilt.edu/company/rigetticomputing (accessed Sep. 25, 2022).

[40] “Building scalable, innovative quantum systems,” *Rigetti Computing*. https://www.rigetti.com/what-we-build (accessed Sep. 25, 2022).

[41] “Story - OxfordQuantumCircuits,” Jan. 15, 2020. https://oxfordquantumcircuits.com/story, https://oxfordquantumcircuits.com/story (accessed Sep. 25, 2022).

[42] “Oxford Quantum Circuits raises £38m Series A round,” *Sifted*, Jul. 05, 2022. https://sifted.eu/articles/oxford-quantum-circuits-series-a/ (accessed Sep. 25, 2022).

[43] “Technology - OxfordQuantumCircuits,” Jan. 15, 2020. https://oxfordquantumcircuits.com/technology,

https://oxfordquantumcircuits.com/technology (accessed Sep. 22, 2022).

[44] "Oxford Quantum Circuits - Q&A - Nanoscience," *Oxford Instruments*. https://nanoscience.oxinst.com/blog/oxford-quantum-circuits (accessed Sep. 25, 2022).

[45] OQC, "OQC first European quantum company on Amazon Braket - OxfordQuantumCircuits," Feb. 28, 2022. https://oxfordquantumcircuits.com/oqc-first-european-quantum-on-braket, https://oxfordquantumcircuits.com/oqc-first-european-quantum-on-braket (accessed Sep. 25, 2022).

[46] "Amazon Braket Python SDK." Amazon Web Services, Sep. 13, 2022. Accessed: Sep. 25, 2022. [Online]. Available: https://github.com/aws/amazon-braket-sdk-python

[47] "Amazon Braket supported devices - Amazon Braket." https://docs.aws.amazon.com/braket/latest/developerguide/braket-devices.html (accessed Sep. 25, 2022).

[48] "Construct circuits in the SDK - Amazon Braket." https://docs.aws.amazon.com/braket/latest/developerguide/braket-constructing-circuit.html (accessed Sep. 25, 2022).

[49] "Run your circuits with OpenQASM 3.0 - Amazon Braket." https://docs.aws.amazon.com/braket/latest/developerguide/braket-openqasm.html (accessed Sep. 25, 2022).

[50] "Introduction — OpenQASM Live Specification documentation." https://openqasm.com/intro.html (accessed Sep. 25, 2022).

[51] Bradben, "What are the Q# programming language & QDK? - Azure Quantum." https://learn.microsoft.com/en-us/azure/quantum/overview-what-is-qsharp-and-qdk (accessed Sep. 25, 2022).

[52] Bradben, "Quantum Development Kit Libraries - Azure Quantum." https://learn.microsoft.com/en-us/azure/quantum/user-guide/libraries/ (accessed Sep. 25, 2022).

[53] "Cirq," *Google Quantum AI*. https://quantumai.google/cirq (accessed Sep. 25, 2022).

[54] "quantumlib/Cirq." quantumlib, Sep. 24, 2022. Accessed: Sep. 25, 2022. [Online]. Available: https://github.com/quantumlib/Cirq

[55] dougfinke, "Cirq Quantum Software Framework Review," *Quantum Computing Report*, Jan. 02, 2019. https://quantumcomputingreport.com/review-of-the-cirq-quantum-software-framework/ (accessed Sep. 25, 2022).

[56] C. Gidney, "Stim: a fast stabilizer circuit simulator," *Quantum*, vol. 5, p. 497, Jul. 2021, doi: 10.22331/q-2021-07-06-497.

[57] F. Frachon, "The Azure Quantum ecosystem expands to welcome Qiskit and Cirq developer community," *Microsoft Azure Quantum Blog*, Oct. 07, 2021. https://cloudblogs.microsoft.com/quantum/2021/10/07/the-azure-quantum-ecosystem-expands-to-welcome-qiskit-and-cirq-developer-community/ (accessed Sep. 25, 2022).

[58] "Qiskit Overview." https://qiskit.org/overview/ (accessed Sep. 25, 2022).

[59] "Continuing the journey to frictionless quantum software: Qiskit Chemistry module & Gradients framework," *IBM Research Blog*, Oct. 29, 2020. https://www.ibm.com/blogs/research/2020/10/qiskit-chemistry-module-gradients-framework/ (accessed Sep. 25, 2022).

[60] P. Smith-Goodson, "IBM Creates Significant Competitive Advantages With Qiskit Runtime Updates," *Forbes*. https://www.forbes.com/sites/moorinsights/2022/05/02/ibm-creates-significant-competitive-advantages-with-qiskit-runtime-updates/ (accessed Sep. 25, 2022).

[61] "D-Wave Ocean Software Documentation — Ocean Documentation 5.4.0 documentation." https://docs.ocean.dwavesys.com/en/stable/ (accessed Sep. 25, 2022).

[62] "Welcome to the Docs for the Forest SDK! — pyQuil 2.6.0 documentation." https://pyquil-docs.rigetti.com/en/v2.6.0/ (accessed Sep. 25, 2022).

[63] "Quantum++." softwareQ Inc., Sep. 13, 2022. Accessed: Sep. 25, 2022. [Online]. Available: https://github.com/softwareQinc/qpp

[64] V. Gheorghiu, "Quantum++: A modern C++ quantum computing library," *PLOS ONE*, vol. 13, no. 12, p. e0208073, Dec. 2018, doi: 10.1371/journal.pone.0208073.

[65] "Quantum JavaScript (Q.js)." https://quantumjavascript.app/ (accessed Sep. 25, 2022).