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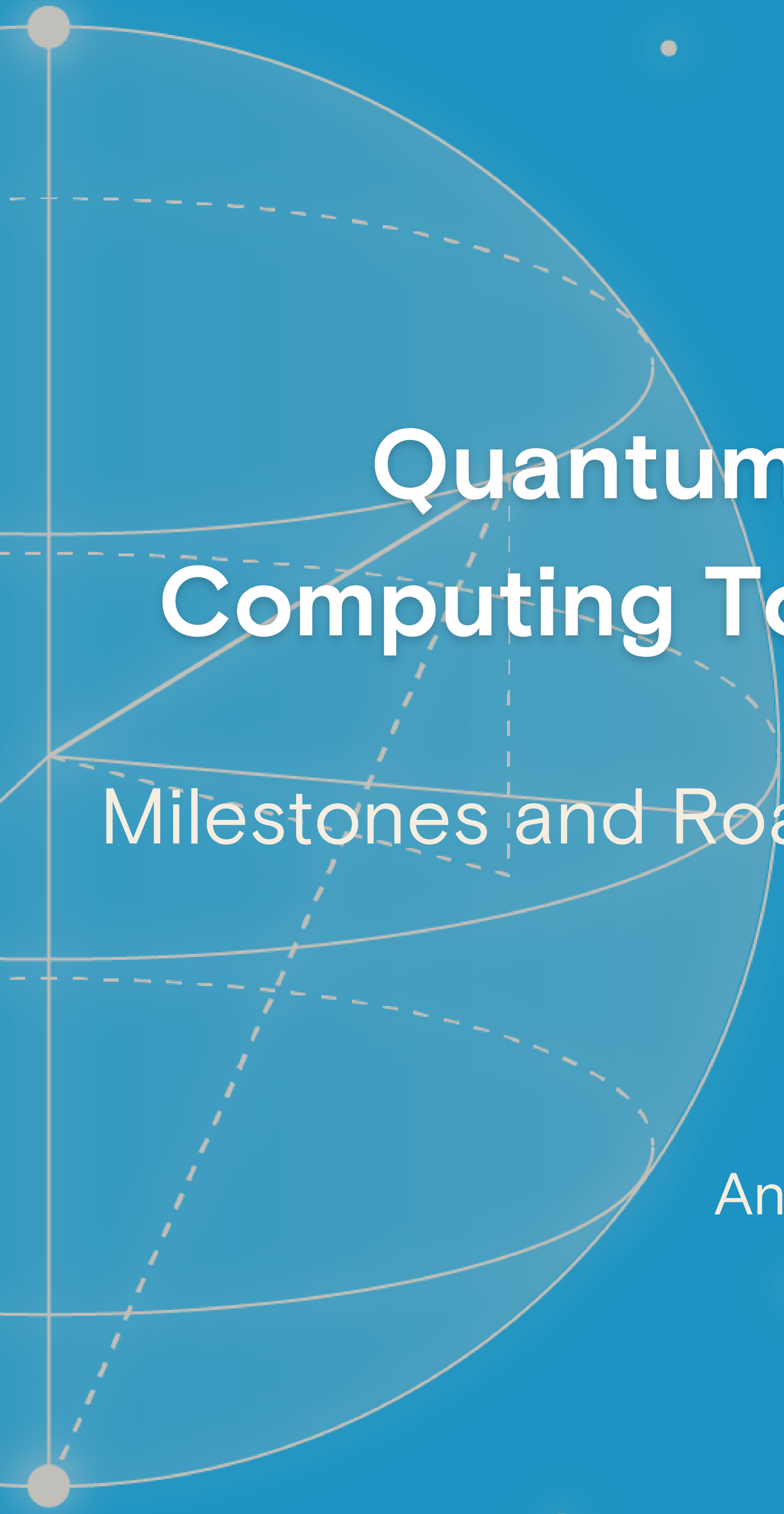

Quantum Computing Today:

Milestones and Roadmaps

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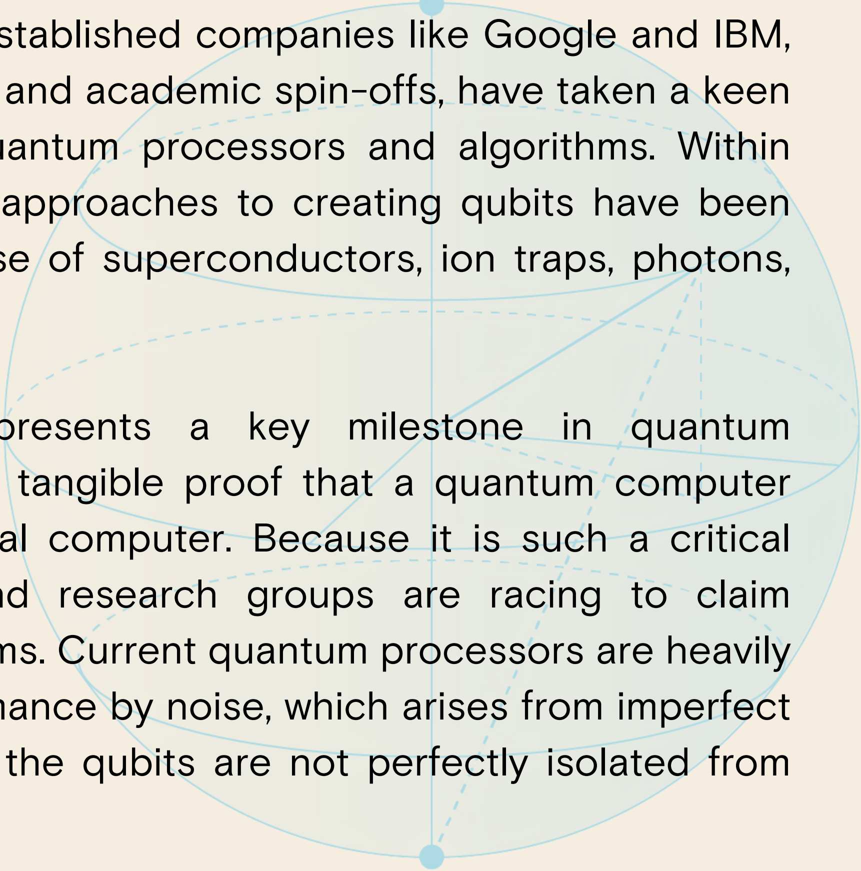
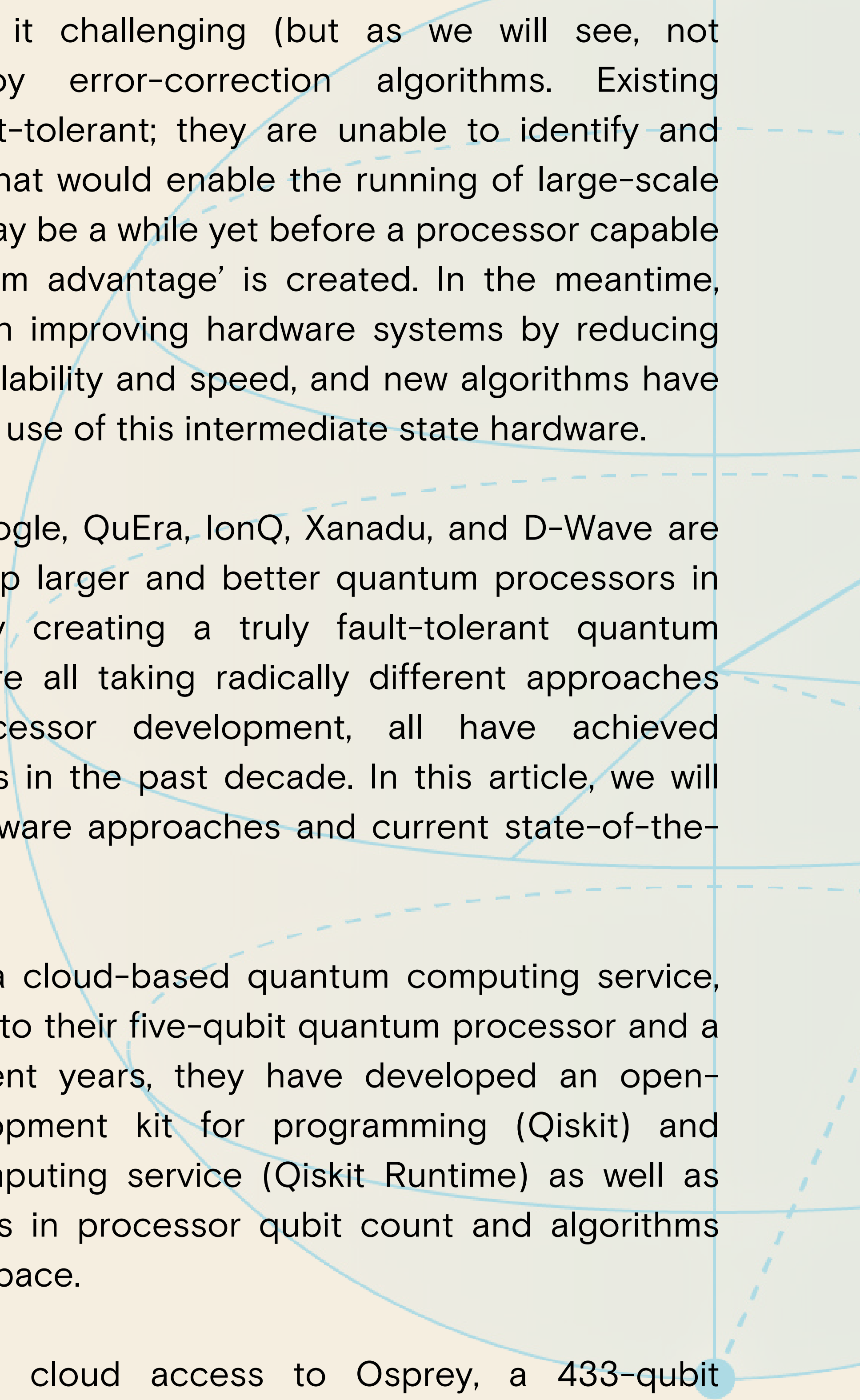
This article provides a quick overview of the most prominent quantum computing companies, summarizing the technologies used and critical milestones achieved.

A quantum computer harnesses the power of quantum mechanics to deliver an unprecedented increase in processing power for special types of mathematical problems. While they will be capable of outperforming tomorrow's supercomputers, they are not likely to replace classical computing for everyday tasks. This is because the problems that quantum computers can tackle potentially more efficiently than classical computers are part of a small, special subclass of existing problems. However, quantum computers promise to accelerate discoveries in many fields, such as finance, pharmaceuticals research, and materials science. Existing quantum processors are already being used to optimize industrial processes, accelerate drug discovery, and to help make financial decisions(1). The secret superpower of a quantum computer lies in its ability to create and manipulate quantum bits, called qubits.

Over the past several years, rapid technological developments and significant investment have accelerated the commercial development of quantum processors. Established companies like Google and IBM, as well as new companies and academic spin-offs, have taken a keen interest in developing quantum processors and algorithms. Within this ecosystem, different approaches to creating qubits have been explored, including the use of superconductors, ion traps, photons, and quantum dots.



Quantum advantage represents a key milestone in quantum computing and would be tangible proof that a quantum computer can outperform a classical computer. Because it is such a critical milestone, companies and research groups are racing to claim advantage for test problems. Current quantum processors are heavily limited in size and performance by noise, which arises from imperfect control systems in which the qubits are not perfectly isolated from the environment.



As a result, the qubit will lose its quantum properties in a process known as decoherence. Currently, we find ourselves in an intermediate era where processors are unable to implement large-scale quantum algorithms with precision, as the high error rates and low qubit count make it challenging (but as we will see, not impossible!) to employ error-correction algorithms. Existing processors are not fault-tolerant; they are unable to identify and correct errors in a way that would enable the running of large-scale quantum algorithms. It may be a while yet before a processor capable of achieving full 'quantum advantage' is created. In the meantime, research has focused on improving hardware systems by reducing noise and increasing scalability and speed, and new algorithms have been developed to make use of this intermediate state hardware.

Companies like IBM, Google, QuEra, IonQ, Xanadu, and D-Wave are all in the race to develop larger and better quantum processors in the hopes of one day creating a truly fault-tolerant quantum computer. While they are all taking radically different approaches towards quantum processor development, all have achieved significant advancements in the past decade. In this article, we will briefly look at their hardware approaches and current state-of-the-art developments.

In 2016, IBM launched a cloud-based quantum computing service, giving the public access to their five-qubit quantum processor and a simulator(2). In subsequent years, they have developed an open-source software development kit for programming (Qiskit) and created a quantum computing service (Qiskit Runtime) as well as achieved new milestones in processor qubit count and algorithms research at a breakneck pace.

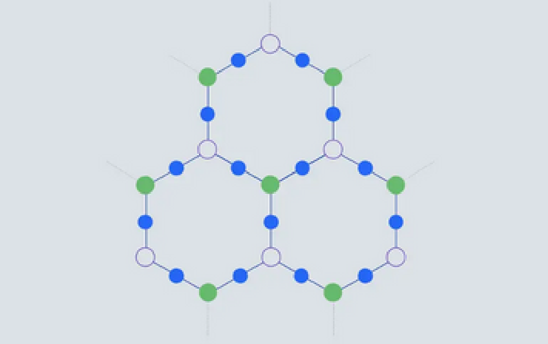
In 2023, IBM unveiled cloud access to Osprey, a 433-qubit processor(3). This more than tripled the number of available qubits compared to their Eagle processor, released in 2021. IBM's quantum processors are based on superconductors, more specifically transmons (the most widely used type of superconducting qubit).

Superconducting qubits are relatively easy to couple to each other and can be controlled using commercial microwave devices. IBM uses a hexagonal layout for all their devices, which reduces errors during the qubit manipulation process. Coupled with improvements in gate design, qubit readout, and control software, the quantum volume (a measure of the size of square quantum circuit that can be computed) of these processors is sufficiently large to permit complex research into algorithms and error control.

Over the years, important research has been conducted on these processors, including one of the first demonstrations of a quantum error correcting code (2015), and the first experimental demonstration of a quantum computer simulating a molecule larger than helium (2017).

Just this year, IBM demonstrated that quantum utility without fault tolerance is possible(4). In this experiment, IBM used their 127 qubit processor to simulate spin interactions and compared these results with a supercomputer. In certain regimes of the problem, while the supercomputer failed to produce accurate results, the quantum computer's results did match analytical approximations, demonstrating that quantum processing could provide greater accuracy and in shorter time-frames. This key milestone in the field of quantum computing indicates that useful quantum processors are within reach and not something that can only be achieved in the million-qubit regime of the far future.

Fig. 1: Visualization of IBM's processor topology which uses the 'heavy hex' lattice (1)

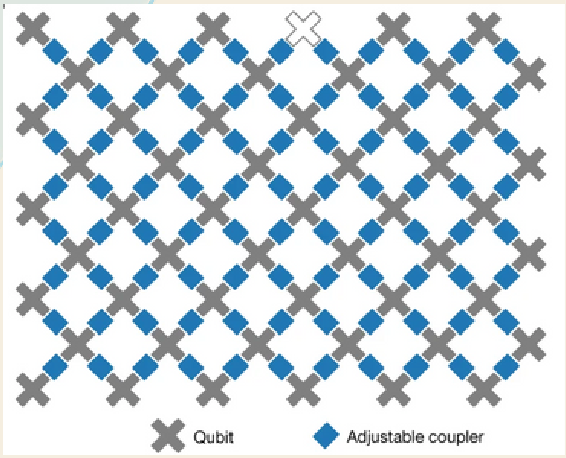


Looking towards the future, IBM believes the path to successful quantum advantage can be achieved with a circuit depth by width of 100 x 100, which represents at least 100 qubits with a depth of 100 gates. They are currently working to achieve this milestone and are hopeful that solid evidence of quantum advantage will emerge in this regime⁽³⁾.

Like IBM, Google also believes that transmon qubits are the way forward. Their most recent development, the new Sycamore processor, consists of a 2-D array of 70 qubits. The hardware layout is chosen to be compatible with an error-correcting code called the surface code⁽⁵⁾.

In 2019, Google claimed to have achieved quantum advantage after demonstrating that their Sycamore processor performed a benchmark calculation faster than the time estimated for a classical computer⁽⁵⁾. In this experiment, Google measured the most likely outcomes of a special type of random number generator for an increasing number of qubits, comparing it to classical simulations and theoretical models until the problem size caused the classical simulation to become intractable. At this point, Sycamore was able to compute the solution to the problem in 200 seconds, while the classical estimate was around 10,000 years. While the scope of their achievement was contested by IBM and other scientists (they claimed a supercomputer would be able to complete the calculation in several days), Google's achievement represents a big step towards the design of useful quantum computers that reliably solve critical problems.

Fig. 2: Visual depiction of Google's Sycamore processor topology, showing a rectangular array of 54 qubits each connected to its four nearest neighbours with couplers⁽²⁾



Quantum error correction (QEC) uses multiple qubits to encode the state of a single qubit (the 'logical' qubit), thereby protecting it from errors. However, for this to work the error rates of each physical qubit must be below the "fault-tolerance threshold". Every individual physical qubit is prone to errors, so the more qubits in a code, the more opportunity for errors. The protection offered by QEC should outweigh the increasing likelihood of errors as the number of physical qubits increases.

Currently, the Sycamore processor has qubit error rates between 1 in 10,000 to 1 in 100, which is far too large to permit error correction(6). In 2023, Google managed to demonstrate that increasing the size of the surface code decreased the error rate of the logical qubit (7) by proving that a logical qubit made from 49 physical qubits outperformed one made of just 17 qubits by 4%. Some of the improvements they made to achieve this milestone include lowering crosstalk between physical qubits, using custom control electronics, and implementing more reliable operations.

Google emphasizes that QEC is central to achieving fault-tolerant computing and is focused on developing ways to implement error-correcting codes on their hardware. Having achieved the milestone of scaling a logical qubit, the next step in their roadmap is to create a long-lived logical qubit, which Google believes will require on the order of 1,000 qubits(8).

A recent development by QuEra, however, demonstrates that modern hardware might be more capable of implementing fault-tolerant circuits than expected. The QuEra team developed a reconfigurable processor based on neutral atom arrays that allows for efficient, parallel operations over entire groups of logical qubits(9). That is, the processor enables the control of individual logic qubits instead of individual physical ones, minimizing the number of control lines and operations required.

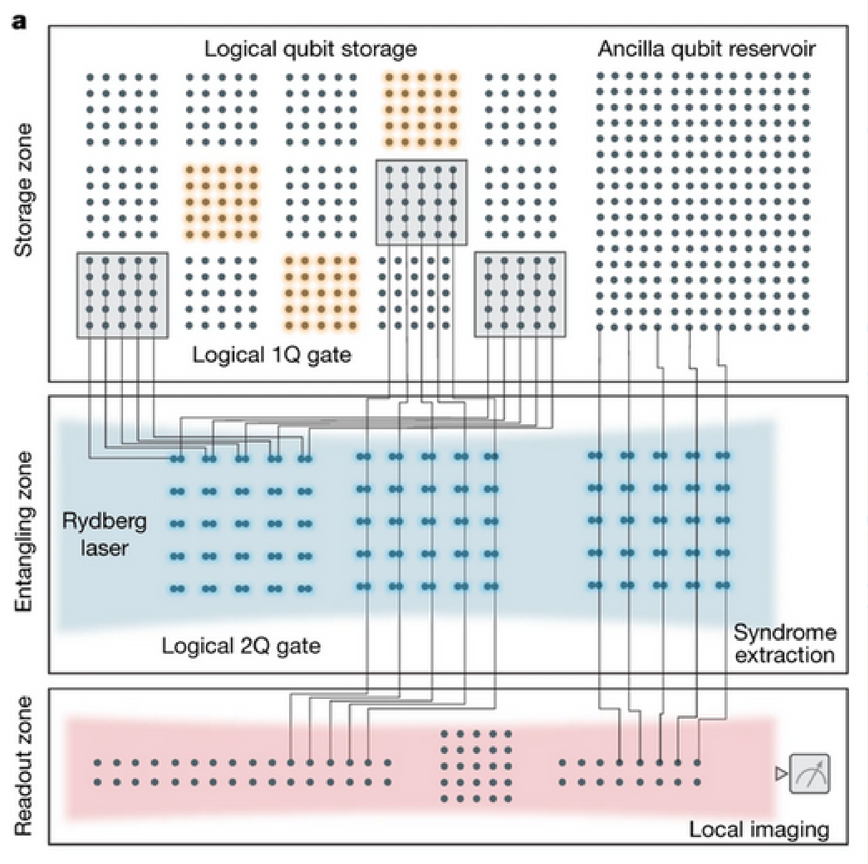


Fig. 3: Schematic of QuEra's logical processor, split into three zones: storage, entangling and readout.(3)

This is an important advancement with regards to scaling qubit systems, as it reduces the control overhead when performing qubit operations. Using this technology, they created 48 logical qubits (using up to 280 physical qubits) and entangled them and studied the performance of various QEC codes on these states. They were able to prove that using larger codes (which can correct for more errors) led to an increase in resistance to quantum errors. They were also able to use these error-controlled qubits to execute complex algorithms, applying over 200 quantum gates to implement logical algorithms that are difficult to simulate classically(9).

This work demonstrates successful error correction and information processing ability using logical qubits and invites further exploration of large-scale logical qubits. A logical next step would be the exploration of a full error-correction cycle on encoded qubits, where further quantum gates are applied to the qubits after error-correction.

Unlike IBM and Google, IonQ is taking a different approach to quantum processor hardware. They use lasers and magnetic fields to create an egg-carton-like lattice that confines charged atoms (ions) in an 'ion trap'. These ions, which are used to encode qubits, are trapped in linear chains. The qubits are individually addressable via a set of laser beams, and information transfer between qubits is accomplished via lattice vibrations (phonons). Trapped ion systems enable all-to-all qubit connectivity, which allows qubits to be entangled without additional swapping operations.

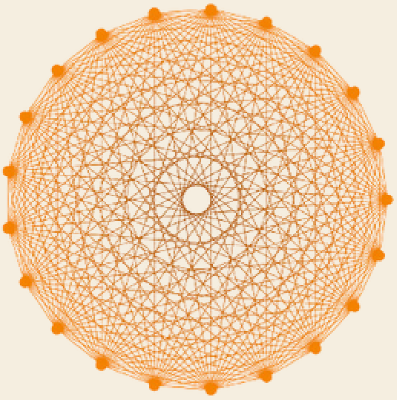
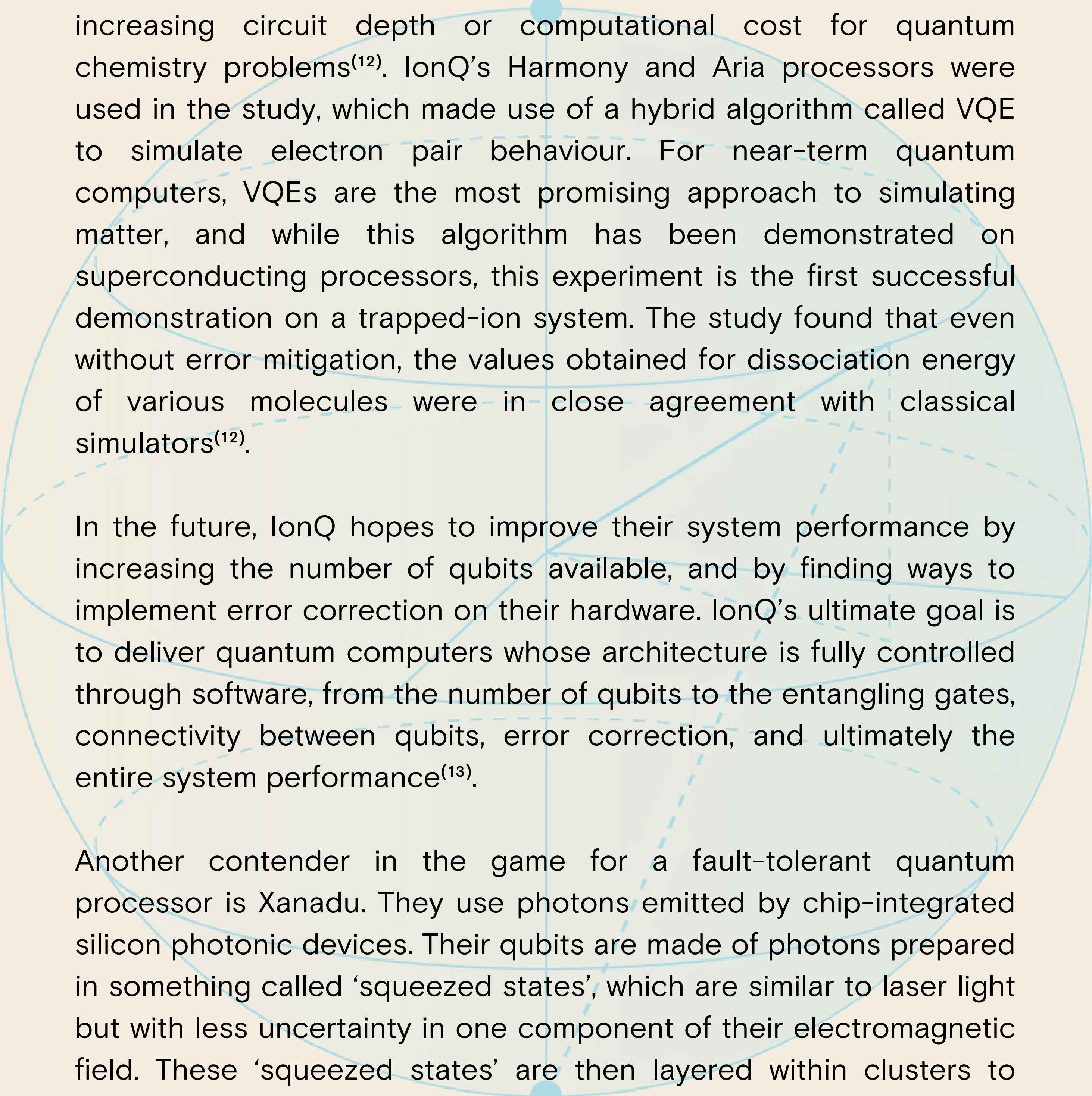


Fig. 4: Artist's depiction of IonQ Aria (Forte predecessor) hardware topology, showing 21 fully-connected, high-quality qubits. All-to-all connectivity, as represented above, enables the system to entangle any qubit with any other qubit with no additional overhead(4).

To date, IonQ has run single-qubit gates on a 79 ion chain, and complex algorithms on chains of up to 11 ions(10). In 2023, IonQ introduced the Forte processor, which contains 32 qubits and the ability to configure more through their software. Since the system is based on linear chains of atoms, a configurable number of ions can be trapped and manipulated using tunable electromagnetic fields. Logic gates can be applied to individual qubits through acousto-optic deflectors (AODs). The biggest advantage of this technology is the ability to adjust the laser beam position to individually address each ion within the chain; this overcomes any distance variations that naturally occur in long chains of trapped ions. Additionally, very accurate qubit control can be achieved with this technology.

IonQ has created a software configurable approach(11), whose goal is to allow everything in the system, from the number of ions to the connectivity of the qubits, to be defined via their software platform.



Aside from developing AOD technology. IonQ is also interested in near-term applications of quantum computing for quantum chemistry. In 2023, they developed a quantum-classical hybrid algorithm that improves the accuracy of quantum circuits without increasing circuit depth or computational cost for quantum chemistry problems(12). IonQ's Harmony and Aria processors were used in the study, which made use of a hybrid algorithm called VQE to simulate electron pair behaviour. For near-term quantum computers, VQEs are the most promising approach to simulating matter, and while this algorithm has been demonstrated on superconducting processors, this experiment is the first successful demonstration on a trapped-ion system. The study found that even without error mitigation, the values obtained for dissociation energy of various molecules were in close agreement with classical simulators(12).

In the future, IonQ hopes to improve their system performance by increasing the number of qubits available, and by finding ways to implement error correction on their hardware. IonQ's ultimate goal is to deliver quantum computers whose architecture is fully controlled through software, from the number of qubits to the entangling gates, connectivity between qubits, error correction, and ultimately the entire system performance(13).

Another contender in the game for a fault-tolerant quantum processor is Xanadu. They use photons emitted by chip-integrated silicon photonic devices. Their qubits are made of photons prepared in something called 'squeezed states', which are similar to laser light but with less uncertainty in one component of their electromagnetic field. These 'squeezed states' are then layered within clusters to create qubits(14). The gates and measurements required to implement any quantum algorithm can be carried out at room temperature, and chips can easily be interconnected through optical networks, making this technology very scalable(15).

Xanadu's recent launch of Borealis, a 216-qubit quantum processor, is the largest photonic quantum computer ever built. More remarkable, however, is that Borealis was able to demonstrate computational advantage in solving a constrained random number generation problem proven to be intractable beyond a certain size on state-of-the-art supercomputers. A demonstration of quantum advantage on this scale had only previously been achieved by Google(5) and a Chinese research team(16). It was estimated that this problem would require over 9,000 years to be solved classically, while Borealis executed the feat in a mere 36 microseconds(17).

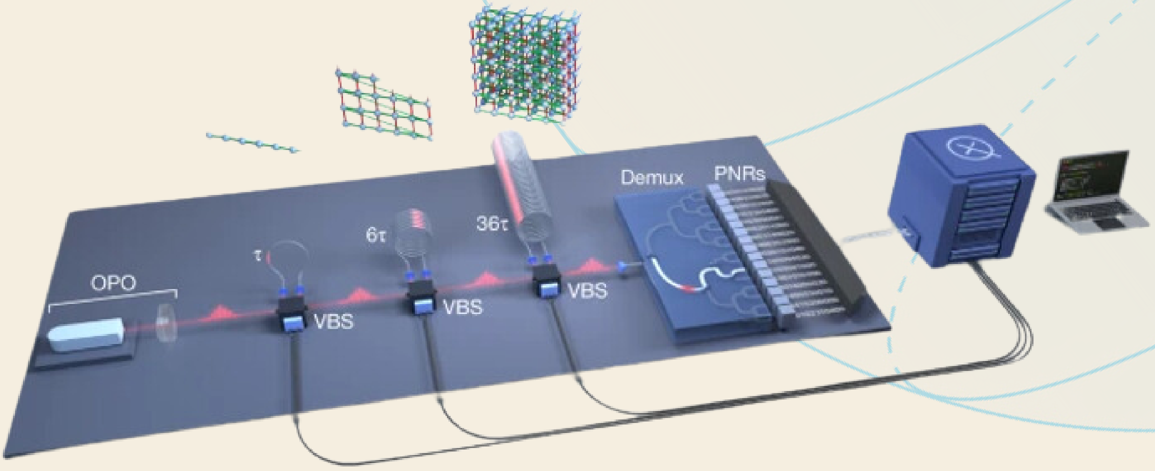


Fig. 5: A high-dimensional fully programmable photonic processor from Xanadu. (5)

Another crucial milestone the Borealis processor met was the first photonic computer with fully user-configurable gates, accessible to anyone via cloud computing. Some of Xanadu's future goals include improving their 'squeezed states', which will permit them to both encode qubits and perform error correction. Some of their current work centers around implementing quantum algorithms on their existing devices, and devising error-correcting codes compatible with scaling their photonic architecture(18).

Unlike the previous companies, D-Wave is not creating a gate-based quantum computer but rather a quantum annealer. While they employ a different computational approach, geared toward solving mainly optimization problems, they still make use of superconducting circuits.

In this case, D-Wave uses superconducting loops to encode a qubit state. The system will begin in the lowest-energy state of the initial Hamiltonian (a function that represents the total energy of a system). The system then evolves in time, and the Hamiltonian of the problem of interest is introduced into the system via magnetic fields that act like couplers and biases. Eventually, the system will settle into the lowest energy state, providing a solution to the problem.

D-Wave's most recent processor, the Advantage, contains 5,000+ qubits with 15-way connectivity. Their patented topology, called Pegasus, contains 27 unit cells on a diagonal grid, plus partial cells around the perimeter(19). This enables higher qubit connectivity and more precise control than their previous processors. Additionally, they provide an integrated software platform called Leap that makes use of quantum-classical solvers to solve optimization and combinatorial problems. D-Wave has many industry partnerships with demonstrated performance improvement because of their technological capabilities(20).

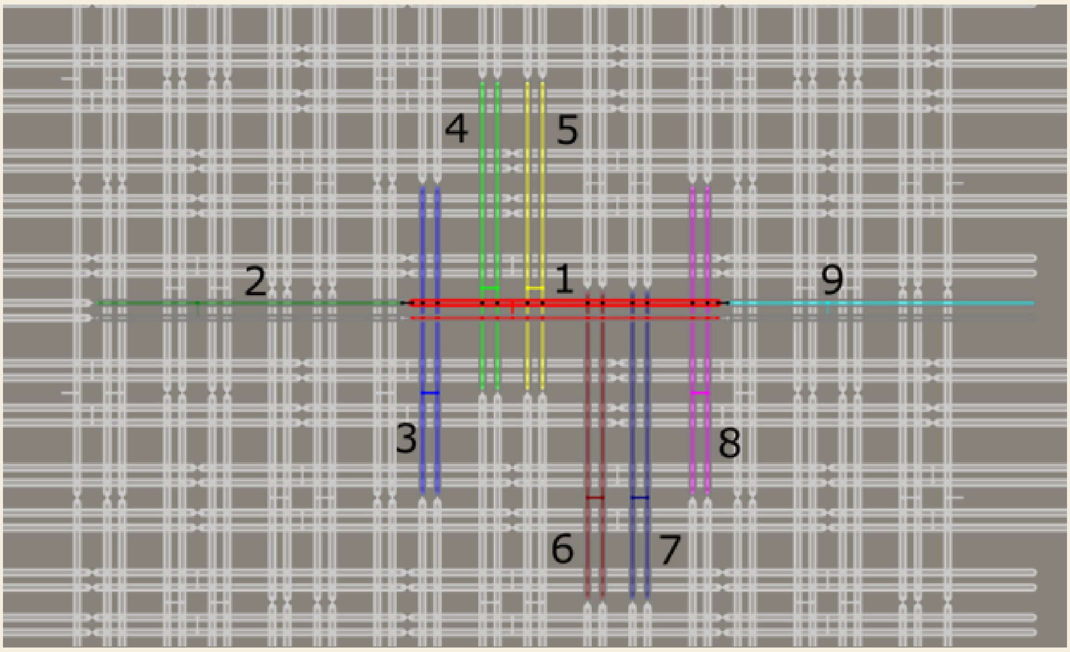
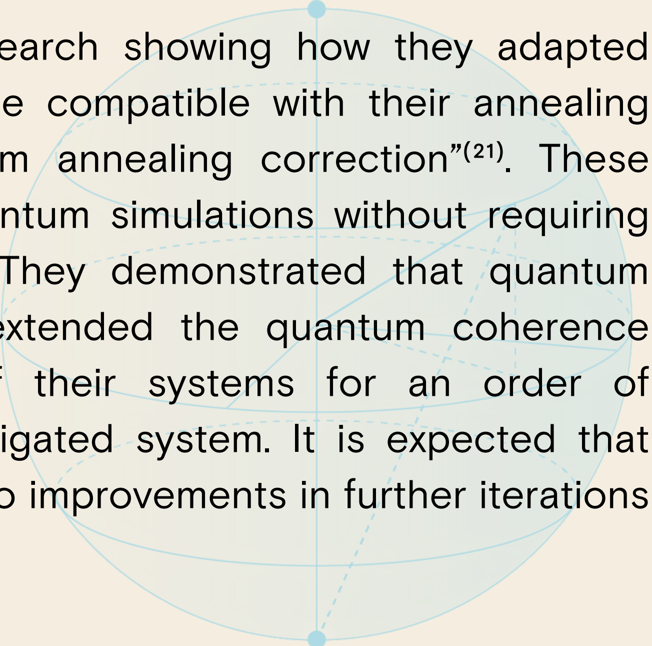


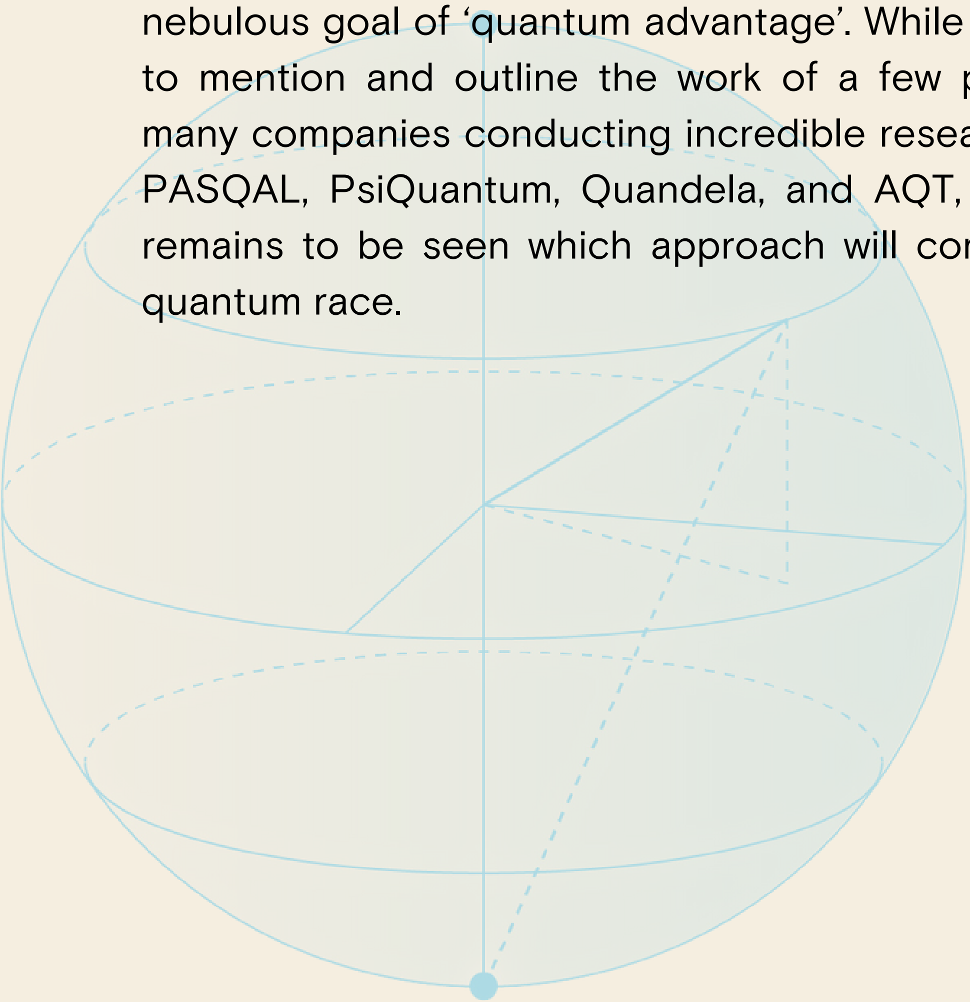
Fig. 6: Pegasus topology with qubits represented as horizontal and vertical loops. Coupled qubits are represented as horizontal and vertical loops: the horizontal qubit in the center, shown in red and numbered 1, with its odd coupler and paired qubit also in red, is internally coupled to vertical qubits, in pairs 3 through 8, each pair and its odd coupler shown in a different color, and externally coupled to horizontal qubits 2 and 9, each shown in a different color. (6)

In 2023, D-Wave published research showing how they adapted error mitigation techniques to be compatible with their annealing processor, terming this “quantum annealing correction”(21). These techniques reduce errors in quantum simulations without requiring any additional qubit overhead. They demonstrated that quantum annealing correction methods extended the quantum coherence (and hence reduced noise) of their systems for an order of magnitude longer than an unmitigated system. It is expected that these techniques will contribute to improvements in further iterations of their Advantage processor.



D-Wave also created a unique metric for measuring quantum performance. This new metric, called ‘quantum utility’, captures the user experience on a quantum processor, and encompasses the ability of the quantum computer to outperform classical alternatives at some tasks of application interest(22).

Overall, companies are making rapid progress in radically different directions as they pursue the highly desirable and somewhat nebulous goal of ‘quantum advantage’. While we have only been able to mention and outline the work of a few popular ones, there are many companies conducting incredible research in the field, such as PASQAL, PsiQuantum, Quandela, and AQT, to name only a few. It remains to be seen which approach will come up victorious in this quantum race.



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