Designing and Building Advanced Quantum Computers*

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Abstract

It has been a while since it was shown in 1994 that quantum algorithms can speed up finding the solution of known problems, i.e., factoring and discrete logarithms [6] or in 1996 the search for a record of a particular property in an unsorted database of N records [7], almost two centuries after the initial empirical evidence in 1801 of the wave-particle duality of the nature of matter and the probabilistic nature of quantum mechanics provided by the Young's double-slit experiment [8]. On the intersection between quantum mechanics and computer science, there has been some advancement describing effects in areas such as algorithms, teleportation, cryptography, and error-correction based on what has come to be called quantum computation [9]. Quantum mechanics for quantum information theory and relevant protocols including teleportation, super-dense coding and entanglement distribution are covered, e.g., in [10]. Introductory treaments about quantum algorithms can be found, e.g., in general in [11, 12, 13] and in particular, for specific areas of application, e.g., in [14, 15]. Some key advantages and limitations of quantum computation compared to classical computation have been presented in [16], i.e., the BQP class of problems that quantum computers can solve efficiently, with BQP=Bounded-error, Quantum, Polynomial time. Among others, we cannot expect that worst-case NP-hard optimization problems be solved efficiently by quantum computers. Appropriate misconceptions of the field are attemtpted to be avoided, e.g., in [17].

Contrary to classical computing that process digital values, i.e., binary digits called bits, quantum computing process data in quantum bits called qubits, i.e., is based on quantum properties of the states of particles including superposition, entanglement, and interference. At any moment in time, a quantum particle is in a probabilistic state of superposition, i.e., a qubit can be considered as assuming a state that is the superposition of the basis states $|0\rangle$ and $|1\rangle$ and the probability of measuring a value of 0 and 1 for that qubit respectively is in general inbetween 0.0 and 1.0 and not precisely at any of those two values. Entanglement is at the heart of the interaction between particles independent of the distance between them, i.e., the state of one particle co-determines the state of another particle. The more qubits are entangled in a quantum computer, the more computations can be performed, and this increase grows exponentially with the number of qubits. Interference between two waves refers to the combination of the waves to increase or decrease the wave amplitudes. In the world of quantum, there is an unavoidable disturbance we cause when we observe an experiment thank to Heisenberg's uncertainty principle. At the quantum scale, we also experience tunnelling phenomena, i.e., particles can travel as waves through potential energy

*This abstract has been granted permission for public release. The author has been designing and building advanced scalable mission-critical concurrent computer systems and custom-chip-interconnects for parallel computers and networks [1], also based on physical modeling of interacting computing cells or artificial neurons, their solid foundations from approximation theory in mathematics, their variational principle formulation and the constrained minimization of norms in Hilbert function spaces, their probabilistic interpretation, processing noisy data in areas like three-dimensional visible surface reconstruction in computer vision [2], advanced automatic robust learning methods in machine learning [3] as well as using multiple System-on-Chip (SoC) [4] and neuro-chips [5] for NASA and DoD classified programs.

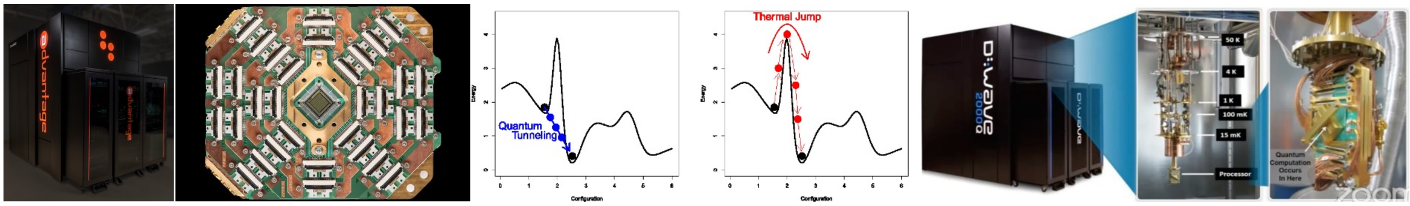

Figure 1: The new generation of quantum annealing computers

barriers and they reach the other side with small probability. Using the Schrödinger equation, the time evolution of the associated wave can be visualized.

While currently designing and building quantum computers, the number of qubits is important and so is their quality as well as the quality of the quantum gates and of the quantum measurements, which process and measure qubits respectively. Both tend to be noisy and limit the scalability of the design and we might need to wait for quantum error-correction and fault-tolerant quantum computation. Other relevant factors are the qubit connectivity and the qubit gate execution time among others. Our expectation in quantum computing is no doubt to be able to solve known problems which cannot be solved with classical computing or to solve them more efficiently. From what we already know, that expectation is based on two assumptions: quantum complexity, i.e., that quantum computing is powerful, and that quantum error correction is feasible, needed to be able to scale current to larger systems capable of solving harder problems than feasible today. During this exploratory time, interesting sub- and affine areas have and are evolving including hybrid quantum/classical optimization engines, quantum annealing computers, digital quantum simulators expected to surpass their analog counterparts for understanding quantum dynamics, quantum error-correction and fault tolerance, quantum cryptography, quantom networks, quantum sensing, and quantum machine learning. It is compelling to think that in general advances in quantum computing, sensing, and networking will evolve concurrently and will benefit from one another [18].

Several companies have started developing quantum chips and computers as well as offering related services including IBM, Google, Amazon, Microsoft, D-Wave, Toshiba, Rigetti, among others. Some developments in two of them are showcased in the sequel. D-Wave Systems' newest integrated circuit, a quantum chip or Quantum Processing Unit (QPU), is the one with the largest number of qubits: at least 5,000. It is the Advantage QPU [19]. The QPU layout is critical to formulate the objective function for the D-Wave annealing quantum computer to solve [20]. The QPU is a lattice of interconnected qubits in the Pegasus graph topology for Advantage QPUs. Qubits connect to others via couplers. The number of couplers per qubit is 15 in Pegasus, The Advantage QPU contains at least 35,000 couplers. The new generation of quantum annealing computers, D-Wave Systems' Advantage, is shown in Figure 1 on the left together with its QPU. In the middle, the effect of quantum tunneling is shown while conceptually minimizing energy levels. On the right, the previous generation, D-Wave Systems' 2000Q, is shown.

After IBM first connected a quantum device to the cloud in 2016, it has been adding new quantum computers and new cloud data centers for its Quantum-centric supercomputing offerings. IBM Quantum System One [21] and IBM Quantum System Two [22] are two generations of its global fleet and its quantum processors have become larger, modular, and more powerful. Like is the case with its competitors' product roadmap, efforts are under way to scale up and connect a growing number of quantum processors through quantum interconnects and mitigate noise-related errors to harness the power of quantum computing to full extent. Figure 2 shows on the left the Heron 133-qubit quantum chip, next new products to be released in 2023 to 2025, e.g., the IBM's Condor, which is a 1,121 qubit chip, scheduled to be released at the end of 2023. Further to the right, an IBM Q System Two is shown, and finally a 100,000 qubit quantum-centric-supercomputer expected to be deployed in 2033 based on foreseen advancements in four areas: quantum communication,

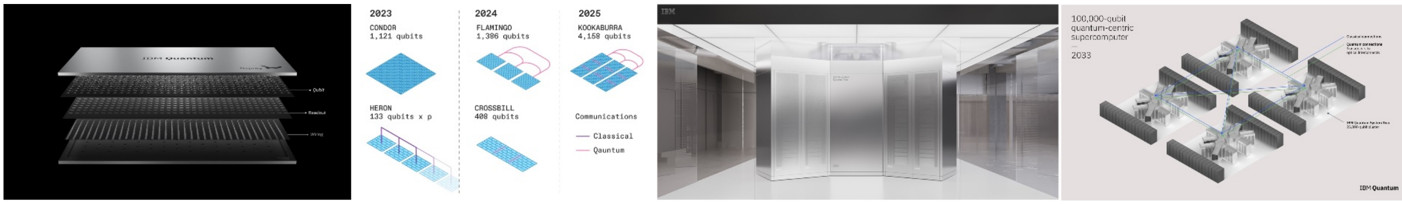

Figure 2: Quantum-centric Supercomputing – Quantum Chips, Communications, Supercomputers

quantum middleware, quantum algorithms and error-correction as well as quantum components with the necessary supply chain.

The U.S. national strategy [23] to support quantum computing states that developments in Quantum Information Science (QIS) [24] can improve the industrial base, generate related employment as well as economic and national security benefits in the U.S. as proven by former achievements in semiconductor mocroelectronics, photonics, the Global Positioning System (GPS) and Magnetic Resonance Imaging (MRI). Current and future government and private industrial investments in QIS can make the impact even broader and deeper. Quantum technologies possess the potential to enhance or upend the current warfighting capabilities for the Department of Defense (DoD) [25]. R&D efforts to advance the development of foundations for quantum networking and the quantum Internet are focused within the strategic vision for that purpose [26]. In this report, innovative design approaches to build next generation quantum computers are presented.

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