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Survey

A Survey on quantum computing technology[☆,☆☆]

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ABSTRACT

The power of quantum computing technologies is based on the fundamentals of quantum mechanics, such as quantum superposition, quantum entanglement, or the no-cloning theorem. Since these phenomena have no classical analogue, similar results cannot be achieved within the framework of traditional computing. The experimental insights of quantum computing technologies have already been demonstrated, and several studies are in progress. Here we review the most recent results of quantum computation technology and address the open problems of the field.

Contents

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1. Introduction

Quantum computing technology offers fundamentally different solutions to computational problems and enables more efficient problem-solving than what is possible with classical computations. The experimental results are promising, and quantum computers may be available commercially within a few years [1–10]. One of the most famous algorithms that demonstrate the power of quantum computers is Shor's prime factorization algorithm [11]. The difference between the power of classical and quantum computing is demonstrable via the breaking speed of the Rivest–Shamir–Adleman (RSA) algorithm [12]. Solving this computational problem requires billions of years in a traditional computational setting, while in theory, a quantum computer can solve it within a few hours [11,13]. In 1994, this algorithm caused the "big bang" of quantum computations and paved the way for the development of quantum computing technology and the evaluation of quantum computers [14]. Quantum computers integrate several different elements—from a functional point of view, such elements are similar to traditional functional ones (registers, gates, memories, buses, CPUs, storage devices), but in the physical layer, the structures of classical and quantum devices are fundamentally different. In a quantum computational framework, the quantum operations are applied on quantum registers. In the quantum register, quantum states formulate quantum superposition, while in a quantum circuit, the quantum states are entangled. These phenomena lead to a fundamentally different system characteristic than what is present in a traditional computer. Besides these, quantum hardware restrictions such as the no-cloning theorem also require different circuit design technologies since a quantum state cannot be simultaneously present in more than one quantum gate [5,10].

A quantum computer has reversible quantum gates that perform a unitary operation on the quantum systems. Quantum computers are working today, but currently we have only a few quantum computer devices in a laboratory environment [1,3–8]. However, several new fields and interesting results have recently emerged that can significantly boost these developments. The large-scale quantum computers are realized in a distributed setting, where smaller quantum computers communicate with one another via a quantum bus. These physically large quantum computers can also be shrunken into small-sized devices via new technologies in the next few years. The situation is very similar to the evolution phases of classical computers both in size and performance.

The most recent research papers and results of quantum computation technology are reviewed here. All sections also address the open problems of the field. State-of-the art references are summarized in the *Related Work* subsection at the end of each section.

The novel contributions of our manuscript are as follows:

- *We review the most recent results of quantum computation technology and address its ongoing issues.*
- *We summarize the most recent and relevant papers on quantum computing technology.*
- *We present the results in a well-structured, easily understandable, and easily acceptable form.*

This paper is organized as follows. In Section 2, we review the fundamentals of quantum computations. In Section 3, we discuss the basic quantum hardware elements. In Section 4, we review the results of large-scale quantum computations. In Section 5, quantum algorithm implementations are summarized. Finally, in Section 6, we conclude the paper.

2. Quantum computations

Quantum computers are based on the fundamental concept of quantum information. In these computers, information is represented by quantum states, and with the exploitation of quantum effects provided by quantum mechanics (such as quantum superposition, quantum entanglement, quantum interference, the no-cloning theorem, decoherence [14–18] etc.), quantum computations can be performed in a quantum computer. In the physical layer, quantum systems can manifest in several different ways (atom energy levels, spin, polarization). A general quantum system refers to a d-dimensional quantum system (for a qubit system, $d = 2$), and therefore, a quantum register (a set of n quantum states) in a superposition allows us to represent d^n possible classical values simultaneously. In quantum circuit computations, the quantum states are naturally modeled as entangled systems; thus, the state of each quantum system depends on the other.

Quantum computations are based on the fundamental concept of reversible computation. In theory, in a reversible computation, the complete initial state can be recovered from the output state [19]. Reversible circuits can also be designed for classical systems [20] such that the number of inputs and outputs of a reversible gate must be equal, and the mapping of a particular input onto a given output must be one-to-one. These rules must also be satisfied for a quantum computation system; thus, the input quantum states of a quantum circuit evolve reversibly via unitary operations. Practically, such reversibility is achieved by a series of quantum gates (for example, applying a second NOT gate – a quantum gate that negates the input – on the output of the first NOT gate recovers the original input, etc.). The temporary quantum systems in a quantum computation setting are called ancilla states, which are neglected as the output is realized. Finally, a measurement is applied on the quantum register to extract a classical numerical value for further calculations.

Quantum algorithms utilize the fundamentals of quantum computational complexity. Several quantum algorithms have been proposed so far, whose general conclusion is that utilizing the effects of quantum mechanics would result in a significant speedup (exponential, polynomial, superpolynomial) over the classical algorithms. Besides this (as demonstrated in the prime factorization problem), it is implied that several problems currently intractable via classical algorithms can be solved via quantum algorithms.

For the basic requirements on the physical implementations of quantum computers, the DiVincenzo criteria [21] establish the fundamental guidelines. These criteria imply the requirement of extensible quantum registers, the initialization of the quantum registers to a known state, the requirement of a universal gate set to run arbitrary quantum algorithms on the quantum computer, and requirements on the coherence time and fidelity to perform long processes, and the results of the quantum computations have to be extractable from the quantum computer via measurements. These are the fundaments of the practical implementation of any quantum computation.

The conceptual diagram of the evolution of quantum computing technology is depicted in Fig. 1. In the functional layer, the aims of classical and quantum computation technology are similar, but in the physical layer, these fields are completely different. The physical foundations of quantum computing technologies are laid down by the DiVincenzo criteria, which are supplemented with particular physical layer attributes. From quantum computing technology, quantum computers are derived with particular conditions on the physical layer attributes of quantum registers, gates, circuits, and memories

The problem of quantum computational complexity has been analyzed from several different aspects. In [22], the authors studied the computational complexity of linear optics and provided new

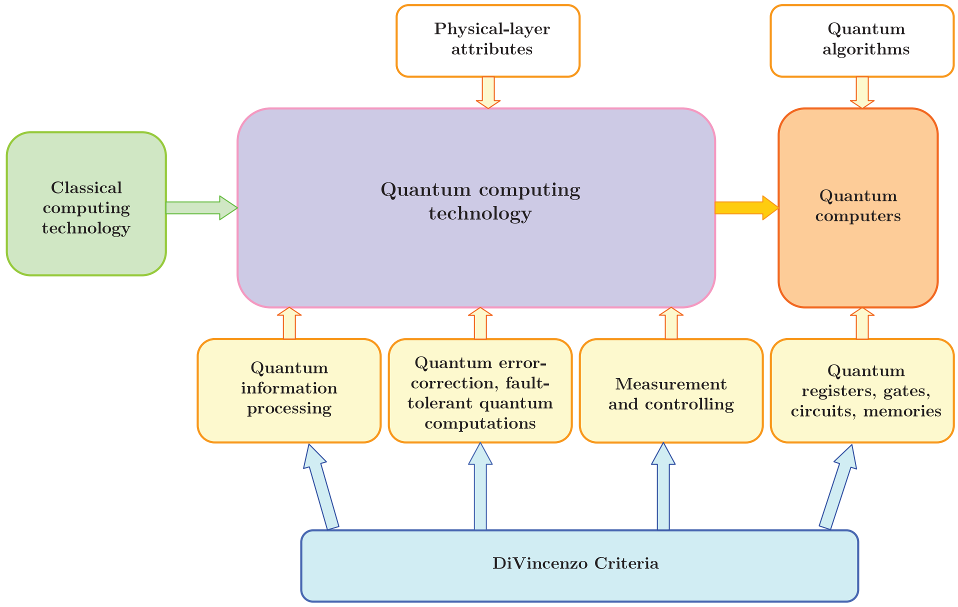

Fig. 1. The conceptual diagram of the evolution of quantum computing technology from classical computing technology. Quantum computers employ the results integrated by quantum computing technologies.

evidence that quantum computers cannot be efficiently simulated by classical computers. The authors also defined a model of computation in which identical photons are generated, sent through a linear-optical network, and then nonadaptively measured to count the number of photons in each mode. They also studied the prospects for realizing the model using current photonics and optics technology. The authors concluded that the proposed model can solve sampling problems and search for problems that are classically intractable.

Aaronson in [23] studied the so-called "learnability" of quantum states. As shown in this work, a quantum state can be characterized by using a number of measurements that grows only linearly with the number of quantum states. The author analyzed the complexity of quantum tomography and showed the possibility of a new simulation of quantum one-way communication protocols by the framework. The paper also analyzed the problem of using a trusted classical advice to verify an untrusted quantum advice.

2.1. Related work

For some books on the fundamentals of quantum computations and information, see [17] and [14,15], while for the main attributes of quantum communication networks, see [9]. Deutsch's fundamental article on quantum theory and the universal quantum computer can be found in [24]. For Feynman's article on the question of simulating quantum computations with traditional computers, see [25]. For the details of the so-called no-cloning theorem, see [26]. For quantum computation problems, see [27]. For a study on the methods and attributes of maintaining coherence in quantum computers, see Unruh's paper from 1995 [28]. For a fundamental work on quantum coding, see [29]. For a discussion of the strengths and weaknesses of quantum computing, see [30]. A fundamental article on quantum complexity theory is found in [31]. For DiVincenzo's seminal paper on quantum computations from 2000, see [21]. For Shor's major study on prime factorization by a quantum computer, see [11]. A great review on quantum algorithms can be found in [32]. For a study on quantum algorithms for algebraic problems, see [33]. For a paper on some recent progress in quantum algorithms, see [34]. An account of the role of entanglement in quantum-computational speed-up can be found in [35]. For a study on matrix product states, projected entangled pair states, and variational renormalization group methods for quantum spin systems, see [36]. For an examination of the problem of temporally unstructured quantum computation, see [37]. The topic of universal blind quantum computation is discussed in [38]. The problem of multiparty delegated quantum computing is reviewed in [39]. For a survey on the subject of quantum simulation, see [40].

3. Building blocks of quantum computers

To discuss the most recent updates regarding the fundamental building blocks of quantum computers, we use the following classification: quantum gates, quantum memories, quantum CPUs, quantum controlling and measurement, and quantum error-correction tools.

3.1. Quantum gates

The quantum gates of a quantum computer perform unitary operations on quantum states. The Toffoli and Fredkin quantum gates [14,15,17–19] are three-bit gates and are essential since any quantum circuit can be decomposed into a set of Toffoli gates or Fredking gates and can also simulate NOT or CNOT (Controlled-NOT) gates. In other words, either gate can be used to realize universal quantum computations [18]. Since quantum gates are reversible, the ancilla states are cleared, and only the valuable outputs are kept.

In the physical layer, the quantum gates can be realized by ion traps, superconductors, linear optic tools, diamonds, quantum dots, donor-based systems, or topological quantum computing elements, see the related references in the Related Work subsection. Handling the errors of the quantum gates for practical implementations requiring efficient quantum error-correction codes is still an open problem [8,10,41–52].

In [53] the authors studied the achievable quantum advantages with shallow circuits. As the authors have found the constant-depth quantum circuits are more powerful than their classical counterparts. As the authors concluded that any classical probabilistic circuit that solves that particular problem must have depth logarithmic in the number of input quantum states. The authors also found that this problem can be solved with unit certainty by a constant-depth quantum circuit. This quantum circuit has to contain only one- and two-qubit gates acting locally on a two-dimensional grid, which represents a practically implementable gate model structure.

In [54], the authors studied the power of IQP (instantaneous quantum polynomial-time) circuits in the presence of some physically motivated constraints. The results are particularly important, since it is hard to simulate classically an IOP circuit. In this work the authors found that there exists a family of IQP circuits that can be implemented on a square lattice of n qubits with a particular depth. They also found that if an arbitrarily small constant amount of noise is added to each qubit there exists a polynomial-time classical algorithm that can simulate sampling from the resulting distribution.

In [55], the authors studied the design methods of high-fidelity three-qubit gates (Toffoli, Controlled-Not-Not and Fredkin), These quantum gates are particularly important for quantum error correction and experimental quantum information processing. The proposed model is based on the fundamentals of machine-learning. As the authors have found, the procedures are applicable to a system comprising three nearest-neighbor-coupled superconducting artificial atoms. The authors concluded that the proposed scheme achieves 99.9% fidelity. This result is particularly convenient since it is a threshold fidelity for fault-tolerant quantum computing.

3.2. Quantum memories

In quantum circuit computations, quantum memories are formulated by n stationary quantum states. The quantum memories store these quantum systems in a quantum register for information processing.

Several different concepts exist in the literature for the realization of quantum memories. An interesting approach is topological quantum memory [56], which is achieved via an array or torus of quantum states. These quantum systems are entangled in some patterns to formulate a stable logical quantum system.

Regarding the physical implementations of quantum memories, improving the memory lifetimes are still an open problem [8,57–64], - however the results are encouraging. A room-temperature quantum bit memory exceeding one second has been demonstrated in [60], while in [61], a large-scale quantum-computer architecture has been proposed with atomic memory and photonic interconnects.

For the discussion on quantum random access memory, see [59]. As the authors defined, a quantum random access memory (qRAM) uses n qubits to address any quantum superposition of N memory cells. The authors proposed an architecture that exponentially reduces the requirements for a memory call. As the authors found, the results allows to construct a more robust qRAM algorithm and also leads to an exponential decrease in the power needed for addressing. The work concluded with a quantum optical implementation.

The exponential capacity of associative memories under quantum annealing recall is studied in [65]. In this work the authors showed that using quantum annealing for recall tasks endows associative memory models (that models can store a sublinear number of memories in some theoretical models) with exponential storage capacities. The authors also demonstrated the application of their scheme via the Dwave processor that provided a programmable quantum annealing device.

The optimization of dynamical decoupling for quantum memory via recurrent neural networks is studied in [57]. In this work the authors utilized the methods of traditional machine learning that are based on recurrent neural networks to optimize dynamical decoupling sequences. As the authors note, these decoupling method is a relatively simple technique for suppressing the errors in quantum memory. The authors showed that at the present of some prior knowledge and with some conditions on the iteration procedure, the analyzed models are useful for error correction in quantum memories.

In [66] a definition of quantum memristors (resistors with memory whose resistance depends on the history of the crossing charges) is included. The decoherence mechanism in the proposed model is controlled by a continuous-measurement feedback scheme. The authors also demonstrated that memory effects actually persist in the quantum regime, and the superconducting circuits are ideal for their practical implementation. As the authors concluded, the introduced model of quantum memristor can be used as a building block for neuromorphic quantum computations, and quantum simulations of non-Markovian systems. The quantum memristors are resistive quantum elements retaining information of their past dynamics [67]. In [67], the authors analyzed the quantum memristors implementations using superconducting circuits. The authors introduced a quantum device whose memristive behavior arises from quasiparticle-induced tunneling when supercurrents are canceled. As the authors have introduced a model for the quantification of quantum memory retention, and concluded the hysteretic behavior is achievable via currently implementable measurement procedures in superconducting quantum circuits. In [68], an analysis of qubit-based memcapacitors and meminductors is proposed. As the authors found, the capacitive and inductive devices offer remarkable functionalities for quantum computations (superconducting charge and phase qubits are quantum versions of memory capacitive and inductive systems). As it is shown in this work, the qubit-based memcapacitors and meminductors exhibit unusual hysteresis curves for some special inputs. As a main result of this paper, the set of known memcapacitive and meminductive systems can be extended to qubit-based quantum devices.

3.3. Quantum CPUs

Quantum CPUs use a quantum bus for the communication between the functional elements of a quantum computer. From a computing perspective, quantum CPUs can be approached through the building blocks that formulate it: quantum adders. Several different reversible quantum adder types have been defined, see quantum Fourier-transform-based adders, linear-time adders, quantum carry-save adders, carry-lookahead adders, conditional-sum adders, quantum carry-select adders, quantum carry-ripple adders [19] to realize quantum computations in different architectural models. The quantum versions of the classical adders can also be made for quantum computations, with reversible structure and parallel implementations. The quantum adders are all reversible and use ancilla quantum states, but they are equipped with different working mechanisms, circuit depths, latencies, and performance; thus, the realization of their cooperation brings up several open problems [69–77].

For the parallelization of the quantum circuits, two basic networks models were defined in [19]. The first network model allows long-distance communication between a set of quantum states (set of states that are involved in the quantum computations). Meanwhile, the second model allows only local communications; it is precisely possible only between the nearest neighbors in a linear layout [9,19]. The performance of the various quantum adders was characterized in these network models, and it has been concluded that the performance of the different configurations is close to each other. For the implementation of the quantum communications between the quantum CPU and the functional elements of the quantum computer, the different experimental quantum error-correction methods can be used [19]. By theory, the performance of a quantum circuit is denoted by $\mathcal{O}(\cdot)$, and because of the nature of signal propagations, the latency of any circuit is limited to $\mathcal{O}\left(\sqrt[D]{n}\right)$ in an n-bit system, and with D-dimensional structure (practically, $D = 3$).

In [19], five different qubus interconnect topologies were analyzed using Shor's prime factorization algorithm. For the basic gate structure of the quantum prime factorization algorithm, see Fig. 2. The quantum algorithm aims to increase the probabilities of the solutions (red dots) in the quantum register A.

As it has been concluded in [19], the quantum carry-ripple adder provides the best performance for a wide range of parameters. As it is concluded in this work, the small nodes (up to five logical qubits) and a linear interconnection network provide adequate performance; more complex networks are unnecessary as the number of bits of the factorized number reaches several hundred bits. Regarding the performance of these quantum adders, in this work it also has been concluded that these adders makes possible to factorize a 6000-bit number one million times and thirteen thousand times faster than it is possible by the BCDP (Beckman–Chari–Devabhaktuni–Preskill) modular exponentiation algorithm.

In [70] the authors also studied the properties of quantum adders, specifically the method of protected state transfer using an approximate quantum adder. In this work the authors defined a decoherence protected protocol for transmitting photonics quantum states over depolarizing quantum channels. The studied protocol was implemented by an approximate quantum adder engineered through spontaneous parametric down converters. As the authors concluded a higher success probability can be achieved via the method than by distilled quantum teleportation protocols for distances below a threshold. In [72], the authors studied the approximate quantum adders with genetic algorithms. Particularly, the authors proposed the theoretical aspects of approximate quantum adders, and defined an optimization method that is based on genetic algorithms. As the authors have found the results makes possible to improve the achievable efficiency and fidelity of some previous protocols. The authors practically implemented an approximate quantum adder using the IBM Quantum Experience. As the authors concluded the approximate quantum adders can help to enhance quantum information processing.

In [78], a method for quantum state transfer via noisy photonic and phononic waveguides is studied. The authors defined a protocol in which a quantum state of photons stored in a first cavity can be faithfully transferred to a second distant cavity via an infinite one-dimensional waveguide. As the authors found this transfer is possible while the transferred information being immune to arbitrary noise (e.g. thermal noise) injected into the waveguide. The authors also studied a cavity QED setup, where atomic ensembles, or single atoms represented the quantum memory. As the authors concluded the proposed models and results can be applied in the various fields of phononic quantum information processing.

In [71], the authors studied the realization of quantum autoencoders using quantum adders with genetic algorithms. As the authors stated, there exists a useful connection between approximate quantum adders and quantum autoencoders. As the authors found, it is possible to develop optimized approximate quantum adders using genetic algorithms. As the authors have concluded, the results also have several practical consequences, since quantum autoencoders can be implemented for a variety of initial states, and quantum autoencoders can be designed via controllable quantum platforms.

In [73], the authors studied the problem of space-efficient design for reversible floating point adder in quantum computing. As the authors emphasized, reversible logic has crucial significance in experimental low-power computing and quantum computing. The authors defined a space-efficient reversible floating-point adder for quantum computers. The proposed model can be used for binary quantum computation, and to improve the designs of the expensive units. The authors proposed techniques for the cost reduction, and for the fault-tolerant designs for the circuits.

In [79], the competing and cooperating technological trends related to experimental quantum computing and quantum computer implementations are studied. As it is concluded here, classical computers will still play a relevant part, however the classical computations are limited by thermodynamics and by the nature of atomic matter and quantum effects.

3.4. Controlling and measurement

The appropriate control mechanisms are a necessity for quantum state manipulations, readout, error-correction processes, and fault-tolerant quantum computations.

Relevant progress has been made since the ion trap-based implementations [10,61,80–90], such as superconducting quantum circuits [1,4,8,42,67,91–97], linear optics [10,98–118], topological quantum computing [43,47,52,119–130], quantum dots [75,77, 131–138], donor-based quantum implementations [10,62,69,138–146], anyon-based quantum computing [10,96,123,126,130,147, 148], and others (see Related Works).

An important open problem in this fields is the preparation of quantum systems for the computations [149–153], as well as the experimental realization of the measurements [48,49,101,113, 154–164] that extracts valuable information from the quantum states.

In [151] the authors studied the practical superposing of two pure quantum states with partial prior knowledge. The results are particularly important in experimental quantum information processing since generating superposition of any two unknown pure states is a challenge since it can be achieved only with some prior knowledge about the input states but only in a probabilistic way. The apriori knowledge is represented by the overlap between the two unknown states with respect to some given referential state. In [151], the authors implemented the probabilistic protocol of superposing two pure states in a three-qubit nuclear magnetic resonance system. They also studied the feasibility of the protocol by preparing a families of input states, and determined the average fidelity between the prepared state. Since the achieved fidelity was high, the authors have also concluded that the proposed implementation can be extended to more complex situations and to complex quantum circuits.

In [149], the authors also studied the problem of superposing unknown quantum states. Particularly, in this work the authors defined an experimentally feasible protocol to superpose multiple pure states of a d dimensional quantum system. The authors also proposed a practical realization on a two-qubit NMR (nuclear magnetic resonance) quantum processor.

In [165] the authors studied some quantum sampling problems, particularly focusing on boson sampling and quantum supremacy. The authors gave a summary on the arguments that are in use to deduce when sampling problems are hard for classical computers to simulate, particularly focusing on boson sampling. The authors gave a conclusion on these classes and reviewed the recent experimental realization connected to quantum supremacy in boson sampling.

In [166], the authors studied the application of differential equations in photonic quantum information processing. The authors introduced a model for the realization of photonic quantum circuits whose dynamics is determined by some differential equations. As the authors have concluded, the studied model enables the implementation of quantum feedback and feedforward without requiring any intermediate measurements in the quantum circuit. The results concluded, the proposed results represent a promising way towards chip-based integrated quantum control.

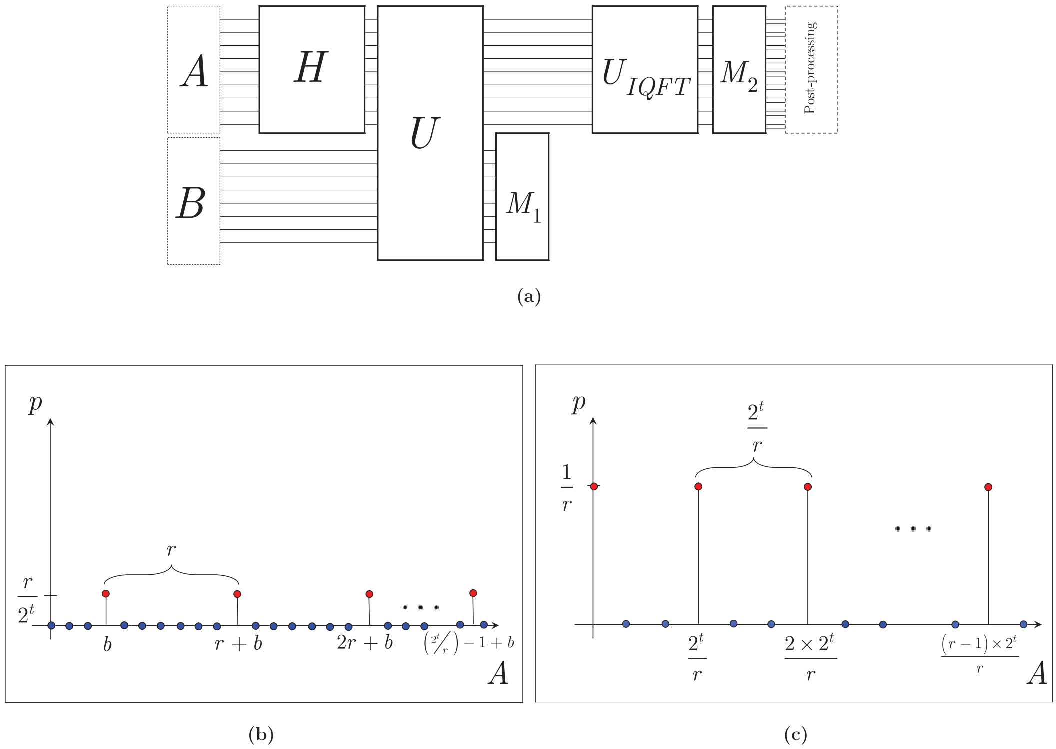

Fig. 2. The conceptual model of Shor's prime factorization algorithm. (a) The quantum circuit of the factorization algorithm. The quantum circuit consists of two quantum registers: the first quantum register A (depicted by the dashed box) contains t qubits; the second quantum register B (dashed box) contains n qubits. First, the superposition of the qubits of register A is prepared via the H Hadamard operation. Then, a U unitary operation is applied that is required for the period-finding method. Next, the qubits of register B are measured via the M_1 measurement operator. Afterward, a second unitary operation U_{IQFT}, the inverse quantum Fourier transformation (*IQFT*), is applied on quantum register A. Finally, the qubits of A are measured by the M_2 operator. (b) The state of register A after M_1 but before U_{IQFT}. (c) The state of register A after U_{IQFT}. Before U_{IQFT}, the p probabilities of the solutions (depicted by red dots) in A are low, $p = r/2^t$ (the nonsolutions are depicted by blue dots, and b is a constant), where r is the period. After U_{IQFT}, the values of p are increased to $p = 1/r$. After the second measurement M_2, some postprocessing steps (dashed box) need to determine r from the measurement result.

In [167], a machine-learning-based model is studied for the prediction and real-time compensation of qubit decoherence. The authors applied some techniques from traditional control theory and traditional machine learning to predict the future evolution of the state of a qubit. As the authors concluded, the studied experimental models demonstrate significant improvements in qubit phase stability over the standard measurement-based feedback approaches. As the authors have found the proposed models require no further extensions on the hardware-layer, and also well applicable for qubit systems where the measurement are achieved by projective measurements.

As another application of quantum artificial intelligence in the field of superconducting circuits can be found in [95]. The analysis covers some basic protocols of quantum reinforcement learning using superconducting circuit implementations. It is also assumed in the paper that these superconducting circuits are equipped with feedback-loop control. The paper also defines some diverse scenarios for superconducting circuits.

In [168], the authors studied the determination and correction of persistent biases in quantum annealers. The paper addresses of some performance issues of quantum annealers. The authors defined a strategy to determine and correct persistent, systematic biases between the actual values of the programmable parameters and their user-specified values. The authors also tested their model in experiment using the D-Wave quantum device implementations. The work concluded that the proposed model can enhance the performance of the actual quantum device.

In [169], the authors studied quantum state discrimination using the minimum average number of copies. As the authors stated, in the task of discriminating between nonorthogonal quantum states from multiple copies, the key parameters are the error probability and the resources (number of copies) used. The authors defined a new state discrimination task, since in their framework the average resources are minimized for a fixed admissible error probability. They concluded that this new task is not performed optimally by previously known strategies, and they also derived and experimentally test.

In [152], the authors studied the problem of superposition generation of some unknown quantum states. The authors proposed a theorem that forbids the existence of a universal probabilistic quantum protocol producing a superposition of two unknown quantum states. The paper also introduced a probabilistic protocol for the creating of superposition of two unknown states, such that the quantum states have a fixed overlap with the known referential pure state. As the authors found, the protocol can be implemented on arbitrary Hilbert spaces allowing a wide-range of practical implementations.

In [150], a study on the experimental creation of superposition of unknown photonic quantum states is provided. The authors defined a method for the creation of superposition of arbitrary two unknown photonic qubits as long as they have nonzero overlaps with the horizontal polarization state. As the paper concluded, the average fidelity as high as 0.99, thus a practical implementations could have a significant importance in experimental quantum computations. A possible practical application of the protocol is information compression by coherent superposition.

In [153], the authors added some knowledge to the current results regarding the generation of superposition of two unknown states. The authors showed that in the presence of closed time like curves, it is possible to generate superposition of unknown quantum states and evade the no-go result of [152].

3.5. Quantum error correction

The development of quantum error-correction methods allows us to satisfy the requirements on high fidelity and adequate coherence times in quantum computations. The nature of errors in a quantum computation system significantly differs from that of classical system errors [45]. Different physical technologies were introduced for the various quantum hardware implementations to achieve reliable, fault-tolerant quantum computations, but a universal model for quantum error correction is still an open problem [8,10,41–52].

The quantum error-correction methods generally use the input data quantum states and syndrome quantum states that are used to identify error information. In experimental quantum computations, a distinction exists between the logical and physical representations of quantum states in that a logical quantum system is encoded by several quantum states in the physical layer. The developed quantum error-correction codes (such as designs of topological error correction, etc.) are adaptable for the different requirements of the various physical implementations.

In [46], the authors studied the problem of surface code error correction on a defective lattice. The motivation behind these error correction schemes, as it is also stated by the authors is that the implementations of quantum computers will be susceptible to loss in the form of physically faulty quantum states. The adaptive error correction schemes will therefore have a crucial significance in practical quantum computations and in the implementations of quantum computers. The authors in this work simulated statically placed single-fault lattices and lattices. The authors concluded that a static loss at the periphery of the lattice has less negative effect than a static loss at the center. The authors also analyzed different metrics for predicting quantum chip performance, and they concluded that the depth of the deepest stabilizer circuit in the lattice gave the strongest correlation with post-correction residual error rates. The results are particularly convenient for experimental quantum computations. In [170], the authors studied the problems of state injection, lattice surgery and dense packing of the deformation-based surface code. The authors defined a deformation-based surface code using superstabilizers to detect short error chains connecting the superstabilizers. The results concluded that it is possible to place logical qubits close together in practical quantum computations. The authors also studied the process of conversion from the defect-based surface code, and they introduced a placement design for the deformation-based surface code. The results are particularly convenient for experimental large-scale quantum computations.

In [44], the authors studied the quantum sample complexity of learning with errors. The authors found that there exists an efficient quantum learning algorithm with polynomial sample and time complexity for a learning problem. As the authors have concluded, the results have some implications for cryptography.

In [171], the authors studied the implementation aspects of silicon-based surface code quantum computers. The work focused on the conflict between nanometer separation for qubit–qubit interactions, and proposed a solution for the separation problem by establishing the feasibility of surface code quantum computing using solid state spins. The proposed method utilizes probe spins that are aimed for the mechanical separation, and includes a protocol for error correction due to the spins being imperfectly located. As the authors have concluded, the defined architecture overcomes many of the difficulties facing solid state quantum computing, and provides qubit densities that are several orders of magnitude greater than other systems. In [147], the authors studied the so-called "majorana zero modes" that are quasiparticle excitations in condensed matter systems. These majorana zero modes have a crucial significance since these can be used as building blocks of fault-tolerant quantum computers. In their model, the authors have used the so-called "Coulomb-blockade spectroscopy" in a nanowire segment that results in a superconducting Coulomb island (a "Majorana island"). As the authors have found, the introduced model helps to clarify the trivial-to-topological transition in finite systems and to study the advanced properties of topological protection.

The authors in [8] showed that the lifetime of a quantum bit can be extended with error correction in superconducting circuits. The implemented qubits are encoded in superpositions of Schrödinger-cat states of a superconducting resonator. The practical implementation covers a quantum error correction protocol that uses a feedback control mechanism. In the proposed implementation, the corrected qubit lifetime was 320 microseconds. As the authors have concluded, these results illustrate the benefits of a hardware-efficient qubit encoding rather than traditional quantum error correction schemes.

In [172], the question of quantum supremacy (quantum devices without error correction can perform a well-defined computational task beyond the capabilities of currently available classical computers) is studied. In this work, the authors analyzed the task of sampling from the output distributions of (pseudo-)random quantum circuits. As the authors have found, sampling the distribution classically requires a high-cost numerical simulation of the circuit. This cost is increases exponentially in function of the number of qubits of the system. The authors analyzed quantum circuits up to 42 qubits. As the authors have found, quantum supremacy can be achieved in the near-term quantum devices with approximately fifty superconducting qubits.

In [173], the authors studied the characterization of decohering quantum systems using a machine learning approach. They analyzed the decoherence effects in adaptive characterization processes, where measurement settings are updated via data feedback. As the authors have found, adapting measurements can provide estimates whose error decreases exponentially in the number of measurements. The authors also developed a framework for handling high initial parameter uncertainty and for the presence of imperfections in the readout in decohering quantum systems. In [174], the authors defined quantum autoencoders for efficient compression of quantum data. By theory, the task of an autoencoder is to map the input to a lower dimensional point such that the input can likely be recovered from the mapped point. The authors defined a model of a quantum autoencoder to perform these operations on quantum data. As the authors found, the parameters of the quantum autoencoder can be trained using classical optimization algorithms. The authors also demonstrated the results for the compression of quantum systems.

3.6. Related work

On the fundaments of quantum computation and information see the anniversary edition of [17] in [18]. For the fundamentals of quantum key distribution, see [175], and [176]. On the further properties of quantum adders, see [19]. On the problem of optimal quantum measurements for phase estimation, see [162]. On the problem of quantum-state estimation, see [177]. For Shor's fundamental paper on the problem of decoherence reduction in quantum computer memory, see [64]. For a study on optimal states and almost optimal adaptive measurements for quantum interferometry, see [154]. On the problem of optimal input states and feedback for interferometric phase estimation, see [178]. For a study on maximum-likelihood estimation of quantum processes, see [179]. On the problem of quantum amplitude amplification and estimation, see [180]. On the theory of open quantum systems, see [181]. On the subject of quantum measurement and control, we suggest [164]. For a study on comparing, optimizing, and benchmarking quantum-control algorithms in a unifying programming framework, see [182]. On the problem of optimizing qubit Hamiltonian parameter estimation algorithm, see [183]. On the problem of quantum commuting circuits and complexity see [184].

For the fundaments of fault-tolerant quantum computation by anyons, see Kitaev's paper from 2003 [148]. For a model of a fault-tolerant one way quantum computer, see [185]. For a great paper on the attributes of surface codes and its applications in practical large-scale quantum computation, we suggest [186]. For the fundamentals of topological quantum computation, see [122,123]. In [121], an architectural design for a topological cluster state quantum computer is proposed. For a demonstration of a quantum error detection code using a square lattice of four superconducting qubits, see [42]. A method for detecting bit-flip errors in a logical qubit using stabilizer measurements is proposed in [49]. About the architectures for a quantum random access memory, see [58]. On the robustness of the so-called bucket brigade quantum RAM, see [187]. For a method of characterization of quantum devices with error correction, see [41]. On the problem of protecting entanglement from decoherence using weak measurement and quantum measurement reversal, see [159]. For an experimental demonstration of topological error correction, see [51]. The problem of adiabatic quantum optimization for associative memory recall has been studied in [63]. On the true precision limits of quantum metrology, see [188]. For the practical implementation of high-fidelity single-shot Toffoli gate via quantum control, see [189]. A study on coherent controlization using superconducting qubits can be found in [94]. On the optimal single-shot strategies for discrimination of quantum measurements, see [163]. In [48], the authors studied the estimation of coherent error sources from stabilizer measurements. They analyzed the situations when the qubits of a given graph state have different error channels. As the authors concluded, the possibility of reconstructing the channels at all qubits depends on the topology of the graph state in a non-trivial way. On the subject of optimal quantum measurements of expectation values of observables, see [160].

The problem of quantum computing with an always-on Heisenberg interaction is studied in [190]. In [6], the problem of entanglement-free Heisenberg-limited phase estimation is studied. About the problems of induced coherence, vacuum fields, and complementarity in biphoton generation, see [191]. About the connection of Toffoli and controlled-not gates with universal quantum computation, see [192]. For a study on quantum computation and quantum-state engineering driven by dissipation, see [193]. On the problem of quantum imaging with undetected photons, see [194]. On biomimetic cloning of quantum observables, see [195]. On quantum control experiments for evolutionary multi-objective algorithms, see [196]. About the attributes of adaptive quantum computation in changing environments using projective simulation, see [197]. On the subject of molecular dynamics with on-the-fly machine learning of quantum-mechanical forces, see [198]. On the problem of Hamiltonian simulation with nearly optimal dependence on all parameters, see [199]. The characterization of the so-called forbidden quantum adder can be found in [74].

4. Large-Scale quantum computing

A large-scale quantum computer is desired for the realization of complex quantum algorithms. Compared to traditional transistor technologies, the structural properties of quantum devices require larger physical distances (because of the physical position of quantum states in the space) and therefore larger building blocks in the physical layer. As a consequence, instead of a large quantum computer (macro-architecture), several smaller quantum computers (micro-architecture) will communicate with each other in a particular network structure to realize distributed computations. Since in the physical layer the actual model used for the implementation of quantum error correction determines the possible theoretical architectures, multiple designs exist to realize large-scale quantum architectures. Finding a universal model of large-scale quantum computations is still an open problem [22,61,87,104,186,200–204]. One of the most promising approaches are the theoretical architectures yielded by the topological error-correction framework [43,47,52,119–127,129,130,205], for further results see the Related Works.

4.1. Gate model quantum computers

In gate model quantum computers, the quantum computations are performed by several layers of quantum gates. Each quantum gate performs a unitary operation on the input quantum systems. The gates are applied in several rounds because of hardware restrictions such as the no-cloning theorem that makes it impossible for a given quantum system to participate in more than one quantum gate simultaneously [5]. Current practical implementations of gate model quantum computers (Google, MIT [5,202–204,206]) are based on qubit systems with a particular qubit-to-qubit coupling topology, and the achievable circuit depth depends on the fidelity of the quantum gates.

In [206], the authors defined the so-called Quantum Approximate Optimization Algorithm, which is a quantum algorithm for the efficient solution of combinatorial optimization problems. As the authors defined, the quantum algorithm outputs approximate solutions, and the working mechanism of the algorithm depends on a positive integer. As they stated, the quality of the approximation of the quantum algorithm improves as this positive integer is increased. As the authors defined, the quantum circuit consists of unitary gates whose locality is at most the locality of the objective function (the goal is to find the optimum of the objective functions). As the authors showed, the depth of the quantum circuit grows linearly within their framework. The authors analyzed the performance of the quantum algorithm on regular graphs, and concluded that it offers several benefits over the classical algorithms. In [207], the authors applied the Quantum Approximate Optimization Algorithm to a well-defined combinatorial problem. In the studied model, the input system is a set of linear equations each of which contains exactly three boolean variables and each equation outputs that the sum of the variables mod 2 is 0 or is 1. The authors showed, that their quantum algorithm will efficiently solve the input problem, and provides several additional benefits over the classical algorithms. In [208], the authors studied the relevance of quantum supremacy, using their algorithm called Quantum Approximate Optimization Algorithm. As the authors stated this algorithm is designed to run on gate-model quantum computers. The algorithm takes as input a combinatorial optimization problem and outputs a string. As the authors stated, this output string satisfies a high fraction of the maximum number of clauses. The authors proved that for certain problems the proposed quantum algorithm has well-characterized performance bounds. As the authors also showed the output distribution of the quantum algorithm cannot be efficiently simulated on any classical device. This statement was further verified via the Quantum Adiabatic Algorithm. As the authors concluded, the proposed framework can be run on near term quantum computers and can be used to demonstrate quantum supremacy. In [5], the authors studied the theory of quantum algorithms for fixed qubit architectures. The analysis is based the gate-model quantum computers. The authors developed a method for programming gate-model quantum computers without the requirement of error correction or compilation. As the authors concluded as an important consequence, the number of logical qubits will be equal to the number of qubits on the device. The proposed methods use a sequence of parameterized unitaries that sit on the qubit layout to produce quantum states depending on those parameters. The authors also defined strategies for parameter optimization and studied the performance of the defined algorithms. The results are particularly important for the development of quantum computers, and can be utilized well in the gate-model qubit quantum computer layouts.

In [19] an architecture of a quantum multicomputer is developed. The architecture of the quantum computer was optimized for Shor's factoring algorithm. In the proposed model, the quantum multicomputer is realized via a large number of nodes that are communicating through a quantum-bus (qubus). As the author stated, the primary metric chosen was the performance of the factorization process. As the author found, the quantum modular exponentiation step represents a computational bottleneck in the development of the quantum architecture and it requires a solution. A number of optimization methods have been proposed in the work to reduce the latency and circuit depth. As a final conclusion of the work, these modifications makes possible to achieve the modular exponentiation of an n-bit number with latency $\mathcal{O}\left(n^2 \log^2 n\right)$ or $\mathcal{O}\left(n^2 \log^n\right)$, while the initial latency was $\mathcal{O}\left(n^3\right)$. Some analysis revealed that the proposed quantum circuits can be more than one million times faster in comparison to other exiting methods (the study used a 6,000-bit number for the demonstration).

The model also defined five different qubus interconnect topologies for the construction of quantum computer networks. The work also defined different forms of quantum adder circuits. As the authors concluded the serial links in the quantum multicomputer structure represent an optimal solution, since, as the author concluded, the parallel links would provide only very modest improvements in system reliability and performance.

4.2. Distributed topologies

Because of the physical distance between the quantum states in the space, large-scale quantum computations seem to be realized by distributed topologies [9,10,19]. In a distributed topology, the smaller quantum computers communicate with each other via a quantum bus (implementable by optical fibers, wireless quantum channels, etc.), and the quantum algorithms and error-correction processes are also executed in a distributed manner. It requires not just a well-designed infrastructure but also protocols of the distributed quantum computations, distributed quantum applications, and quantum error correction, as well as distributed quantum control and measurements. Practically, the smaller quantum computers are connected via a particular system area network (SAN). In a SAN model, the quantum computers could have an arbitrary quantum hardware with diverse quantum coding approaches, which are handled and controlled by some appropriate protocols (the model also implements classical protocols). For larger distances, quantum metropolitan area networks (Q-MAN) or quantum wide area networks (Q-WAN) can be constructed.

In [10], the authors studied the models and methods of local and distributed quantum computation. This paper provides a great review on the different construction methods and experimental quantum error correction models that are relevant for the implementation of scalable quantum computing are also studied.

In [80], the authors proposed a model for designing a million-qubit quantum computer. As the authors found, an appropriate balance is needed between the large-scale integration of components in quantum computers and the reliability of hardware technology of quantum computers. As the authors found, this balance can be evaluated by appropriate modeling tools. The authors modeled the execution of quantum logic operations on a realistic quantum hardware with limited computational resources, and provided a performance simulation. The work also demonstrated the results through the Shor algorithm to factor a 1,024-bit number with a baseline budget of 1.5 million qubits. The authors concluded that a trapped-ion quantum computer can factor a 2048-bit integer in less than five months.

In [209], the authors proposed a model for distributed secure quantum machine learning that enables a classical client to delegate a remote quantum machine learning to the quantum server. The authors defined a protocol that assumes a remote small-scale photon quantum computation processor. Since the method is based on the fundamentals of quantum mechanics, the protocol is secure without leaking any relevant information to an eavesdropper. In [210], the authors studied the quantum generalization of feedforward neural networks. The authors used the fundamental result that classical neurons can be generalized to the quantum case with reversibility. In this work the authors showed that these quantum networks can be used to compress quantum states onto a minimal number of qubits, creating a quantum autoencoder, and also useful to discover quantum communication protocols such as teleportation. As the authors concluded, the defined quantum neuron module can naturally be implemented photonically, therefore the model can also be implemented in practice. In [131], the authors studied the feasible implementation of quantum neural networks using quantum dots. The model is based on dipole–dipole interactions. They have found that the proposed implementation is both feasible and versatile. As the authors defined, the physical implementation of framework uses GaAs based quantum dot qubits coupled to a reservoir of acoustic phonons. The authors showed that the quantum coherence in the defined neural networks survive for over a hundred picosec even at liquid nitrogen temperatures (77 K). As they concluded, this result is three orders of magnitude higher than current implementations which are operating at temperatures in the mili Kelvin range.

4.3. Physical implementations

The currently implemented seven quantum technologies (ion traps, distributed and monolithic diamonds, superconductors, linear optics, quantum dots, donor systems, and topological quantum computing) used to realize quantum computers can be classified into four generations [10]. The *first-generation* quantum computers are realized via ion traps, with some KhZ as physical speed and some Hz as logical speed [10,61,80–90]. The footprint ranges of these quantum computers are in mm–cm. The *second-generation* quantum computers are implemented by the distributed diamonds [60,97,211–216], superconducting quantum circuits [1,4,8,42,67,91–97], and linear optical [10,98–118] technologies. These quantum computers could produce MhZ ranges as physical speed, and their logical speed is in the kHz domain, with footprint sizes in μm–mm. The *third-generation* quantum computers are based on monolithic diamonds [51], quantum dots [75,77, 131–138], or donor [10,62,69,138–146] technologies. Their physical layer speed is in the GhZ range, while their logical speed is in the MhZ range, with footprint sizes in nm–μm. The *fourth-generation* quantum computers use the topological quantum computing technology [10,96,123,126,130,147,148] (also referred to as anionic quantum computing [10]). These technologies are currently in development and continuously evolving. An important impact of the fourth generation is that no active quantum error correction is needed since the system is developed to be naturally protected from decoherence. It allows the establishment of reliable quantum computations in practice without dedicated quantum error correction. An open problem in the current fourth-generation implementations is the realization of distributed quantum computing between distant points via anionic particles [96,123,126, 130,147,148]. For the related research results, see the Related Work subsection.

In [7] the authors proposed a practical realization of a scalable Shor algorithm on quantum computers. Due to the fact that several practical implementations of the factorization algorithm have been demonstrated using different quantum computer architectures, the general scalability of the algorithm was still not addressed before this result. The authors demonstrated factoring the number fifteen by seven qubits and four "cache-qubits". As the authors showed the scalable Shor algorithm can be realized by an ion-trap quantum computer with success probabilities 90%.

In [217] the authors proposed a novel model for the design of superconducting flux qubit. As the authors demonstrated, their solution provides broad-frequency tunability, strong anharmonicity, high reproducibility and relaxation times in excess of 40 microsec at its flux-insensitive point. In the developed framework the qubit dephasing at the flux-insensitive point is dominated by residual thermal-photons in the readout resonator. The results provided a revisit for flux qubit to enhance coherence and reproducibility in quantum circuits and quantum computer implementations. In [82], the authors demonstrated a method of engineering a modular quantum computer of any size from ion crystals. Since trapped atomic ions have great importance for the practical development of first generation quantum computers, the study of ion crystals-based solutions have a crucial significance from the perspective of near-future practical quantum computing. The proposed solution also studies the wiring between ion trap qubits, and the aspects of practical implementations such as experimental quantum computing protocols.

In [91], the authors introduced a hardware platform to address the challenge of combination of various quantum elements into a quantum computer. The proposed solution fuses the methods of integrated circuit fabrication and three-dimensional circuit quantum electrodynamics (3D cQED). The authors defined the multilayer microwave integrated quantum circuit (MMIQC) platform to study scalable quantum computing. In [118], the authors studied quantum dots in electrically controlled cavity structures. To goal of the study was to achieve the simultaneous generation of near-unity indistinguishability and pure single photons with high brightness. The authors demonstrated a method for on-demand, bright and ultra-pure single photon generation. As they have found, this type of new generation of sources open the way to a new level of complexity and scalability in optical quantum manipulation.

In [136], a model for an improved operation of exchange-coupled semiconductor quantum dots is presented. As the authors have found, the sensitivity of exchange operations can be reduced, the dephasing effect of charge noise can also be reduced significantly in comparison to operation near a charge-state anti-crossing. The proposed model also allows a performance improvement via rate, therefore the results are particularly convenient for fast quantum operations. In [75], an addressable fault-tolerant qubit model has been introduced that uses a natural silicon double quantum dot with a micromagnet optimally designed for fast spin control. As the authors have found, the model leads to high qubit fidelity (99.6%,) which is the highest reported for natural silicon qubits, and comparable to that obtained in isotopically purified silicon quantum-dot-based qubits. The results are particularly important from the implementation of practical quantum computers, since these result can be applied directly via the current devices.

In [139], the authors demonstrated a method for deterministic, on-demand generation of two-qubit entangled states. The practical implementation is based on electron and the nuclear spin of a single phosphorus atom embedded in a silicon nanoelectronic device. As the authors have found, by sequentially reading the electron and the nucleus the generated entangled states violate the Bell/CHSH inequality. An extension of their model also allows to implement a high-fidelity quantum non-demolition measurement (QND). As the authors have concluded, their experimental results represent a complete control over the two-qubit Hilbert space of a phosphorus atom. In [218], the authors studied the method of Hamiltonian simulation by qubitization. As the authors stated, for a specially given Hermitian operator the problem of Hamiltonian simulation is approximating the time evolution operator at a particular time with a specified error. The authors revealed that this kind of Hamiltonian simulation is possible with a well characterized, optimal query complexity. In [219] the authors showed that if multiple copies of a quantum system with particular density matrix are given, then one can create quantum coherence among different copies of the system to perform quantum principal component analysis. As the authors concluded, it is particularly convenient result for experimental quantum computations, since revealing the eigenvectors corresponding to the large eigenvalues of the unknown state exponentially faster than any existing algorithm. For a study on the advances in quantum metrology, see [220]. As the authors stated, quantum metrology is the study of those quantum techniques that allow one to gain advantages over purely classical approaches. In this work the authors reviewed some of the most promising recent developments in quantum metrology. For a work on the synthesis of arbitrary quantum circuits to topological assembly, see [129]. In this work, the authors proposed a method for the efficient generation of physical quantum circuits and quantum gate implementations for quantum computers. In [221], the authors studied the method of quantum-assisted Gaussian process regression. By theory, the Gaussian processes are a widely used model for regression problems in supervised machine learning. As the authors found, the quantum linear systems algorithm introduced in [222] can be applied to Gaussian process regression. As the authors concluded, it leads to an exponential reduction in computation time in some cases, or a polynomial increase in efficiency is also possible. In [223], a quantum algorithm is defined for linear regression. The quantum algorithm is applied for fitting a linear regression model to a given data set using the least squares approach. As the author stated, contrary to the previous existing algorithms result in a quantum state that encodes the optimal parameters, the proposed quantum algorithm outputs classical values. From the characteristics of the model it follows that by running it once, the fitted model can be completely determined.

4.4. Related works

A fundamental study on quantum computations with cold trapped ions from 1995 is included in [83]. For a basic work on the demonstration of a fundamental quantum logic gate, see [90]. A model of quantum computation with quantum dots has been defined in 1998 in [135]. For the model and attributes of a silicon-based nuclear spin quantum computer, see [143]. For a scheme for efficient quantum computation with linear optics, see [103]. For a study on a one-way quantum computer, see [224]. In [87], an architecture for a large-scale ion-trap quantum computer is defined. For a demonstration of an all optical quantum controlled-NOT gate, see [108]. For the properties of quantum dynamics of single trapped ions, see [88]. For some models of distributed quantum computing, see [225] from 2003. The question whether 'Can quantum mechanics help distributed computing?' is discussed in [226]. On the subject of measurement-based quantum computation, see [156]. An architecture of a quantum multicomputer optimized for Shor's factoring algorithm is developed in [227]. On the requirements for fault-tolerant factoring on an atom-optics quantum computer, see [228].

For a review article on the main attributes of optical quantum computing, see In [109]. For a review on the fundamental photonic quantum technologies, see [110]. The models of fault-tolerant architectures for superconducting qubits are studied in [93]. For an overview on the main attributes of quantum computers from 2010, see [104]. For a work on distributed quantum computation architecture using semiconductor nanophotonics, we suggest [76]. For the fundamentals of quantum error correction, see [45]. On the role of superconducting circuits for quantum information, we suggest [92]. In [87], an architecture for a large-scale ion-trap quantum computer has been defined. A method for the classical control of large-scale quantum computers is discussed in [201]. For a definition of a scalable architecture for a room temperature solid-state quantum information processor, see [51]. In [60], a room-temperature quantum bit memory that exceeds one second is proposed. For the model of a large-scale modular quantum-computer architecture with atomic memory and photonic interconnects, see [61]. This work also proposed a large scale modular quantum computer architecture with atomic memory and photonic interconnects. For a realization on storing quantum information for 30 s in a nanoelectronic device, see [62]. In [84], the authors study the problem of probabilistic quantum gates between remote atoms through interference of optical frequency qubits. On a study on T-junction multi-zone ion trap array for two-dimensional ion shuttling, storage and manipulation, see [85]. In [81], the authors study the problem of high-fidelity transport of trapped-ion qubits through an X-junction trap array. For a discussion on fault tolerant quantum computation with nondeterministic gates, see [105].

For the experimental realization of atomically precise placement of single dopants in silicon, see [146]. In [138], the properties of silicon quantum electronics are reviewed. In [229], some fundamental questions on the building of quantum computers are summarized.

In [114], the problem of so-called ballistic universal quantum computation is studied. For the details of the IBM quantum computer, see [230]. In [113], a method is defined for the measurement of a photonic qubit without destroying the state itself. In [111], the model of silica-on-silicon waveguide quantum circuits is studied. For a survey on silicon quantum electronics we suggest [138]. In [99], a study on the main properties of silicon quantum photonics is proposed. The problem of modular entanglement of atomic qubits using photons and phonons is studied in [86].

A practical implementation on coherent coupling of a superconducting flux qubit to an electron spin ensemble in diamond is proposed in [97]. The attributes of superconducting qubits poised for fault-tolerant quantum computing are studied in [1]. In [42], a demonstration of a quantum error detection code is proposed, using a square lattice of four superconducting qubits. In [133], the authors studied highly efficient single-photon sources based on a quantum dots in a photonic nanowire. In [231], the authors proposed an experimental generation of single photons via active multiplexing. For a discussion on bright solid-state sources of indistinguishable single photons, see [100]. In [107], the problem of active temporal multiplexing of photons is studied. For a study on the effect of loss on multiplexed single-photon sources, see [98].

For a study on the relevance of diamonds in quantum computing, see [112]. For a discussion on arbitrarily complete bell-state measurement using only linear optical elements, see [101]. For a work regarding on-chip manipulation of single photons from a diamond defect, see [102]. In [212], practical implementation for room-temperature entanglement between single defect spins in diamond is demonstrated. A photonic architecture for scalable quantum information processing in NV-diamond is defined in [232]. In [233], a study on nanodiamonds in Fabry–Perot cavities is proposed. The results are particularly important for the implementations of quantum computation, since the negatively-charged nitrogen-vacancy color center in diamond provides a physically realizable platform for quantum computation.

For a discussion on the model of charge-based silicon quantum computer architectures using controlled single-ion implantation see [140]. For a study on quantum entanglement between an optical photon and a solid-state spin qubit, see [216]. In [214], the authors study the problem single-shot readout of a single nuclear spin. In [215], the problem of high-fidelity projective read-out of a solid-state spin quantum register is studied. In [116] the on-chip quantum interference between silicon photon-pair sources is studied. For the practical realization of qubit entanglement between ring-resonator photon-pair sources on a silicon chip, see [117]. In [137], the authors studied the experimental implementation of a two qubit logic gate in silicon. For a demonstration of single-atom electron spin qubit in silicon, see [144]. A demonstration of high-fidelity readout and control of a nuclear spin qubit in silicon can be found in [145]. For an experimental model of spin readout and addressability of phosphorus-donor clusters in silicon, see [69]. In [141], the authors studied the model of surface code quantum computer in silicon.

The two-dimensional architectures for donor-based quantum computing are discussed in [142]. In [211], a practical realization of heralded entanglement between solid-state qubits separated by three meters is proposed. In [134], a layered architecture for quantum computing using quantum dots is defined. For the model of an addressable quantum dot qubit with fault-tolerant control fidelity, see [77]. In [213], a loophole-free bell inequality violation has been proposed using electron spins separated by 1.3 kilometers.

On the relevance of non-abelian anyons and topological quantum computation, see the review paper of [126]. In [119], the problem of fast decoders for topological quantum codes are studied. For a discussion of signatures of majorana fermions in hybrid superconductor–semiconductor nanowire devices, see [96]. On the discussion of topological quantum computing with a very noisy network and local error rates approaching one percent, we suggest [47]. A model for the cross-level validation of topological quantum circuits has been defined in [127]. A study on the fault-tolerant renormalization group decoded for Abelian topological codes can be found in [120]. The problem of mapping of topological quantum circuits to physical hardware is studied in [128]. For a discussion on majorana zero modes and topological quantum computation, see [130]. The problem of minimum weight perfect matching of fault-tolerant topological quantum error correction is analyzed in [43]. For the fundamentals of quantum computation with topological codes, see [124].

In [234], the problem of surface code quantum computing by lattice surgery is studied. In [235], the problem of lower overhead quantum computation is discussed. For a programmable architecture for quantum computing, see [236]. In [201], the problem of classical control of large-scale quantum computers is studied. For the fault-tolerant thresholds for quantum error correction with the surface code, see [50]. In [80], the authors studied the problem of designing a million-qubit quantum computer via a resource performance simulator. In [89], the authors studied the model of a microwave ion trap quantum computer. In [237], the authors studied the problem of resource costs for fault-tolerant linear optical quantum computing. For a compiler for fault-tolerant high level quantum circuits, see [205].

In [238], a layered software architecture for quantum computing design tools has been defined. A method for quantum circuit simplification and level compaction can be found in [239]. A survey on quantum programming languages can be found in [240]. In [241], a scalable quantum programming language has been proposed. A model for software design architecture and domain-specific language for quantum computing has been proposed in [242]. For a quantum computing library for programming purposes see [243]. On the model of repeat-until-success quantum computing using stationary and flying qubits, see [244]. On the problem of scalable error correction in distributed ion trap computers, see [245]. On the problem of distributed quantum computation based on small quantum registers, see [246]. The problem of integrated optical approach to trapped ion quantum computation is discussed in [247]. For a discussion on quantum networks with trapped ions, we suggest [248]. For a study on the recent results of quantum chemistry on a quantum computer, we suggest [249]. On the problem of quantum annealing with manufactured spins, see [250]. On time optimal quantum computation, see [251]. A study on gate-count estimates for performing quantum chemistry on small quantum computers can be found in [252]. On the details of a variational eigenvalue solver on a photonic quantum processor, see [253]. The problem of quantum dynamics of single trapped ions is studied in [88]. On the problem of preparation of thermal states of quantum systems by dimension reduction, see [254]. About the methods of preparing projected entangled pair states on a quantum computer, see [255].

5. Quantum algorithm implementations

Shor's prime factorization algorithm [11] is one of the most important quantum algorithms, and it also serves as a benchmark to characterize quantum computation performance [19]. The prime factorization algorithm has been implemented by different physical approaches with various conditions on scalability level.

Quantum teleportation, quantum Fourier transform, quantum key distribution, quantum communication protocols [256–268], and quantum error-correction methods – which are not computational problems, however – play a crucial role in the realization of distributed quantum computations [9,10,19]. Their practical implementations are essential for any future experimental quantum computations, such as the development of the quantum Internet [269,270]. Some practically implemented quantum algorithms belong to the quantum machine learning field [2].

Quantum programming languages [3,10,236,240,243] are also a distinct field with the purpose of developing appropriate programming languages for quantum computers.

5.1. Large-Scale quantum computations

Another important field is that of classical algorithmic tools designed to control large-scale quantum computations [127,129,205,238,239,241,242,252]. These include the mechanism and processes of distributed quantum computing such as quantum error correction in the nodes, protocols for communication between the quantum nodes, information transfer between the nodes and the quantum bus, decoding processes, optimization procedures, and many more. In both the implementation of quantum algorithms and the use of various quantum communication protocols, classical information will likely be present in the system as an auxiliary element [119,120,245]. Therefore, these quantum algorithms and methods are will be rather mixed "quantum–classical" systems, with the augmentation of classical information processing, than purely quantum systems. For further references see the Related Work subsection.

In [271] the authors proposed strategies for quantum computing molecular energies. The model is based on the application of the variational quantum eigensolver (VQE) algorithm to the simulation of molecular energies. The VQE algorithm utilizes quantum computers to efficiently determine values with a classical optimization routine in order to approximate ground state energies of quantum systems. As the authors have concluded, the defined strategies make possible to reduce the quantum circuit depth for the implementation of the algorithm and improve the optimization of the wavefunction.

In [272], the authors studied the possibilities of practical optimization for hybrid quantum–classical algorithms. The authors analyzed the required number of repetitions that are required for a precise estimation, since the state preparation and measurement phases have to repeated multiple time. Their analysis is based on a particular class of hybrid quantum–classical algorithms. This class is selected by its well applicability in the field of quantum chemistry and combinatorial problems. The work also studied the application of quasi-Newton optimization methods in hybrid algorithms.

5.2. Computational problems

In [273], the authors studied the quantum gradient descent for linear systems and least squares. The authors defined a quantum linear system solver that outperforms the current methods for large families of matrices. The proposed scheme is based on an improved procedure for singular value estimation. The authors provided the quantum method for performing gradient descent for cases where the gradient is an affine function, and in this case the cost of the method can be exponentially smaller than the cost of performing the step classically. They also provided applications of their quantum gradient descent algorithm. In [274], the authors studied the problem of quantum gradient descent and Newton's method for constrained polynomial optimization. The problem of gradient descent algorithms is to determine a local minima by moving along the direction of steepest descent. In the Newton's the problem solution uses curvature information which can be used to improve the convergence process. In this work, the authors defined the quantum versions of these iterative optimization algorithms. The authors applied them to some optimization problems, and as they concluded the quantum algorithms provide an exponential speed-up over classical algorithms.

In [275], the authors analyzed the unified quantum no-go theorems and the transform of quantum states in a restricted set. The authors defined general quantum transformations forbidden or permitted by the superposition principle. The authors introduced the so-called no-encoding theorem. This theorem forbids linearly superposing of an unknown pure state and a fixed state in Hilbert space of finite dimension. The authors proposed two general forms include the no-cloning theorem, the no-deleting theorem, and the no-superposing theorem as special cases. The authors also defined a unified scheme for presenting perfect and imperfect quantum tasks (cloning and deleting).

A demonstration of a small programmable quantum computer with atomic qubits is reported in [3]. The authors demonstrated a five-qubit trapped-ion quantum computer that can be programmed in software to implement arbitrary quantum algorithms by executing any sequence of universal quantum logic gates. As the authors have concluded the reconfiguration of the gate sequences provides a way to implement algorithms without altering the hardware. The authors implemented the Deutsch–Jozsa and Bernstein–Vazirani quantum algorithms with average success rates of 95% and 90%, respectively. They also performed a coherent quantum Fourier transform (QFT) on five trappedion qubits for phase estimation and period finding. As the authors concluded the implemented model can be scaled to larger numbers of qubits, and can be further expanded by connecting several modules. The results have great significance from the perspective of practically implementable quantum computations.

In [276] the authors studied the fast graph operations in quantum computation that uses the connection between entangled states and graph theory. In this work the authors analyzed this connection and showed that it can be used in the reverse direction to yield a graph data structure. The authors also defined efficient algorithms for transformation and comparison operations on graphs. As the paper concluded, there exists no classical data structure that can achieve similar performance for the set of operations studied.

A method for an automated search for new quantum experiments is introduced in [277]. The authors provided a scheme for the development of an algorithm that can determine new experimental implementations for the creation and manipulation of quantum systems. The provided results of the paper range from the first implementation of a high-dimensional Greenberger–Horne–Zeilinger (GHZ) state to asymmetrically entangled quantum states. The authors also concluded that new types of high-dimensional transformations can be determined that can perform cyclic operations.

In [278] a survey on some known quantum algorithms is given. The analysis focuses on the applications of the algorithms and not the technical description. The author also discusses some near-term applications of quantum algorithms in experimental quantum computing. In [279], the authors introduced a protocol that models the biological behaviors of individuals living in a natural selection scenario. As the authors found, the engineered evolution of the quantum living units represents the fundamental features of life. The authors concluded that the results could be useful in the realization of artificial life and embodied evolution with quantum technologies. In [280], the authors defined a method for quantum singular value decomposition of non-sparse low-rank matrices. The authors defined a quantum algorithm to exponentiate non-sparse indefinite low-rank matrices on a quantum computer. As the authors concluded, in some cases the proposed methods allows to find the singular values and associated singular vectors exponentially faster than it is possible via classical algorithms.

In [125], the authors defined quantum algorithms for topological and geometric analysis of data. The authors developed quantum algorithms for the identification of some topological features for information extraction processes applied on large data sets. The proposed quantum algorithms also can be used for finding eigenvectors and eigenvalues. As the authors concluded, the defined quantum algorithms can provide an exponential speedup over classical algorithms for topological data analysis.

In [281], the authors studied the methods of efficient phase estimation. The authors defined an efficient adaptive algorithm for phase estimation. The main novelty of the proposed solution is that their algorithm does not require that the user infer the bits of the eigenphase in reverse order. The defined method directly infers the phase and estimates the uncertainty in the phase directly from experimental data. As the authors concluded, the introduced algorithm can be applied in the presence of substantial decoherence with the same speed as the original phase estimation methods. In [282], the authors studied the quantum perceptron models, and analyzed how quantum computation can provide improvements in the computational and statistical complexity of the perceptron model. The authors defined two quantum algorithms for this purpose. As the authors found, improvements can be achieved through the application of quantum amplitude amplification to the version space interpretation of the perceptron model.

In [283], the authors used the Instantaneous Quantum Polynomial time class of commuting quantum computations to strengthen the conjecture that quantum computers are hard to simulate classically. As the authors found, if either of two plausible average-case hardness conjectures holds, then these class of computations are hard to simulate classically up to constant additive error. The authors also analyzed the problem using spin-based generalizations of the Boson Sampling problem.

In [284], the authors defined quantum algorithms for solving two problems connected to stochastic processes. The first algorithm prepares the thermal Gibbs state of a quantum system, the second algorithm estimates the hitting time of a Markov chain. As the authors concluded, the proposed quantum algorithms are useful for Hamiltonian simulation, spectral gap amplification, and solving linear systems of equations. In [285], the authors studied the problem of digital quantum simulation of many-body non-Markovian dynamics. The authors defined an algorithmic framework for the digital quantum simulation of many-body non-Markovian open quantum systems. As the authors concluded, the proposed method provides a tool for an experimental realization for a variety of problems. In [286], the authors studied the Simulated Quantum Annealing algorithm. This algorithm samples the equilibrium thermal state of a Quantum Annealing (QA) Hamiltonian, and they have concluded that in some cases simulated quantum annealing can be exponentially faster than classical simulated annealing.

In [287], the authors studied the impossibility of classically simulating the so-called one-clean-qubit Computation. By theory, in the model of one-qubit quantum computation, the input state is a completely mixed state except for a single clean qubit, and only a single output qubit is measured at the end of the computing. As the authors found, the proposed results weakens the complexity assumption necessary for the existing impossibility results on classical simulation of various sub-universal quantum computing models. The authors also discussed some experimental implication of the results.

In [288], the limits on fundamental limits to computation are studied. In this work the fundamental limits to computation with respect to manufacturing, energy, physical space, design and verification effort, and algorithms are reviewed. As it is concluded in the paper, engineering difficulties encountered by emerging technologies may indicate yet-unknown limits. In [289], the authors studied the problem of fault-tolerant operations for universal blind quantum computation. As the authors emphasized, blind quantum computation is an appealing use of quantum information technology because it can conceal both the client's data and the algorithm itself from the server. The authors defined a protocol to reduce the client's computational load by transferring the qubit preparation to the server. In the proposed model, for each logical qubit used in the computation, the client is only required to receive eight logical qubits via teleportation then buffer two logical qubits before returning one. As the authors concluded, this protocol can protect the client's fault-tolerant preparation of logical qubits from some attacks.

In [290], the authors studied the problem of simulating chemistry efficiently on fault-tolerant quantum computers. As the authors emphasized this kind of analysis is important since quantum computers can in principle simulate quantum physics exponentially faster than their classical counterparts. The authors defined methods for chemical simulation algorithms computationally fast on fault-tolerant quantum computers. The authors discussed some methods for constructing arbitrary gates which perform substantially faster than some circuits. As the authors concluded, for a given approximation error, arbitrary single-qubit gates can be produced fault-tolerantly in an efficient way. On quantum metropolis sampling, see [291]. In this work, the authors analyzed that how a quantum version of the so-called Metropolis algorithm can be implemented on a quantum computer. As the authors stated, the Metropolis algorithm permits to sample directly from the eigenstates of the Hamiltonian and thus evades the some problems that crucial in classical simulations.

In [292], the authors defined a quantum algorithm for data fitting. As the authors showed, the proposed quantum algorithm can efficiently determine the quality of a least-squares fit over an exponentially large data set. The method is based on the problem of solving systems of linear equations efficiently, which problem was also addressed in [222]. As the authors found, in some cases the algorithm can also efficiently find a concise function that approximates the data to be fitted and bound the approximation error. The authors concluded, in some cases where the input data is a pure quantum state, the algorithm can be used to provide an efficient parametric estimation of the quantum state. As an important practical application of the quantum algorithm with pure state inputs, the authors showed that it can be applied as an alternative to full quantum state tomography given a fault tolerant quantum computer.

In [222], the authors defined a quantum algorithm for linear systems of equations. As the authors stated, the problem of solving linear systems of equations can be significantly improved with the help of quantum computations. The authors considered a case where it is not needed to know the solution itself, but rather an approximation of the expectation value of some operator associated with the solution. As the results concluded the proposed quantum algorithm provides an exponential improvement over the best classical algorithm.

5.3. Quantum machine learning

Since quantum artificial intelligence and quantum machine learning are emerging fields [2], the study of these protocols has a crucial significance for experimental quantum information processing. In [95] the authors studied the implementation of some basic protocols of quantum reinforcement learning using superconducting quantum circuits. Superconducting quantum circuits are provide an implementable technique for the practical realization of quantum computations and quantum information processing. In this work, the authors defined some scenarios for proof-of-principle experiments using the currently available superconducting circuit technologies.

A model for the practical demonstration of the quantum advantages in machine learning in included in [293]. In this work the authors showed that an oracle-based problem (learning parity with noise), can be solved and implemented by a five-qubit superconducting processor. As the authors practically demonstrated that theoretically known results that there is a large gap in query count between the classical and quantum algorithms on a particular oracle. The authors concluded that the achievable gap increased by orders of magnitude as a function of the error rates and the problem size. As the authors have also concluded, complex fault-tolerant architectures needed for experimental universal quantum computing.

In [294], the authors studied quantum recommendation systems. As the authors found, the proposed algorithm provides good recommendations by sampling efficiently from an approximation of a preference matrix. Their method does not require the reconstruction of the entire matrix. As the authors concluded, their scheme is the first algorithm for recommendation systems that runs in time polylogarithmic in the dimensions of the matrix and provides an example of a quantum machine learning algorithm for a real world application.

In [295], the authors studied a quantum–classical deep learning framework for industrial datasets in near-term devices. The authors defined a hybrid quantum–classical framework with the potential of tackling high-dimensional real-world machine learning datasets on continuous variables. In the proposed scheme, the authors used deep learning to extract a low-dimensional binary representation of data. As the authors concluded, the proposed model is suitable for relatively small quantum processors which can assist the training of an unsupervised generative model. The authors also proposed an experimental demonstration on a real-world dataset, and illustrated the proposed concept on a quantum annealer. A method for learning thermodynamics with Boltzmann machines (stochastic neural network in machine learning applications) is proposed in [296]. The authors introduced a Boltzmann machine that is capable of modeling thermodynamic observables for physical systems in thermal equilibrium. As a main novelty of the paper, the authors used unsupervised learning to train the Boltzmann machine on data sets constructed with spin configurations. As the authors concluded, the trained Boltzmann machine can be applied to generate spin states. The authors also showed that this machine can faithfully reproduce the observables of a physical system, and that the number of neurons required to obtain accurate results increases as the system is approaches criticality. In [297], the authors studied the estimation methods of effective temperatures in quantum annealers for sampling applications. The work also extended the analysis to some applications in machine learning. The authors introduced a model to overcome the problem of effectively using a quantum annealer for Boltzmann sampling. Their solution is based on a simple effective-temperature estimation algorithm. The work also provided an analysis on the impacts of the effective temperatures in the learning of a some Boltzmann machines that were embedded on quantum hardware, and defined further algorithmical solutions for the quantum domain. In [298], the authors studied the quantum Boltzmann machine, and showed a new machine learning approach based on quantum Boltzmann distribution. The authors studied the problem of training of quantum Boltzmann machines that is a non-trivial problem. The authors defined bounds on the quantum probabilities that allows us to train it efficiently by sampling. The authors concluded the results with some examples and analyzed the possibility of using quantum annealing processors like D-Wave for the training of a quantum Boltzmann machine. In [299], the authors studied the quantum annealer driven data discovery. The authors defined experiments for quantum annealers and compared the results to the methods of machine learning. The authors studied a binary classifier that utilizes a quantum annealer to produce a more robust class estimator. The authors also provided a detailed discussion of algorithmic constraints and trade-offs imposed by the use of their hardware model.

In [161] the authors studied the models of quantum machine learning that requires no quantum measurements. The authors defined a quantum machine learning algorithm for efficiently solving a class of problems encoded in unitary operations. In the proposed model, an iteration process is defined that uses a quantum time-delayed equation for dynamics feedback such that the method requires no the implementation of quantum measurements. As the paper concluded, the application of time-delayed equations significantly can enhance some methods in experimental quantum machine learning. In [300], the authors studied the methods of quantum-enhanced machine learning. The authors defined an approach for the application of machine learning in quantum information processing. The authors also revealed that it is possible to achieve quadratic improvements in learning efficiency via the model. They also showed that the model makes possible to achieve exponential improvements in performance over limited time periods. As a general conclusion of the paper, the model is well-applicable for a broad class of learning problems in quantum information processing. In [301], the authors studied a fast machine-learning online optimization scheme for of ultra-cold-atom experiments. The authors defined an online optimization algorithm based on Gaussian processes and applied it to optimization of the production of Bose–Einstein condensates (BEC). They utilized the fundaments of machine learning to build up a statistical model of some parameters that are connected to the condensates. They also showed that the internal model developed can be used to determine which parameters are essential in BEC creation which results are particularly convenient for an experimental setting. In [302], the authors studied quantum algorithms for supervised and unsupervised machine learning. Their analysis provides algorithms for cluster assignment and cluster finding. The results are particularly important for quantum artificial intelligence, since Quantum machine learning can provide exponential speed-up over classical learning algorithms.

5.4. Optimization problems

A study on the theory of variational hybrid quantum–classical algorithms can be found in [303]. In this paper the authors extended the general theory of the quantum–classical hybrid optimization algorithm using the framework of the so-called "quantum variational eigensolver" algorithm. The authors suggested algorithmic improvements for practical implementations, and introduced the quantum variational error suppression method that makes possible to suppress the errors in the quantum devices. The paper also defined a method for free optimization techniques, and it concluded that these solutions can reduce the computational costs up to three orders of magnitude over previously used optimization techniques.

A prediction method by linear regression on a quantum computer is studied in [304]. The proposed algorithm of the authors is based on a linear regression model with least squares optimization. As the authors concluded, the results can be accessed via a single qubit measurement, and the runtime is logarithmic in the dimension of the input space.

In [305], the authors defined genetic algorithms to enhance the versatility of digital quantum simulations. The authors found, that genetic algorithms can be used to increase the fidelity of quantum states, and to optimize the resource requirements of some digital quantum simulation protocols. The authors demonstrated the results via a modular gate made out of imperfect quantum gates.

In [306], the authors defined a quantum support vector machine for big data classification. As the authors found, the support vector machine (an optimized binary classifier) can be implemented on a quantum computer. As they showed, the complexity of the quantum algorithm is logarithmic in the size of the vectors and the number of training examples. As they concluded, the quantum algorithm in some cases (if classical sampling algorithms require polynomial time) achieves an exponential speed-up compared to the classical algorithms.

In [307], the authors studied the Solovay–Kitaev algorithm and its optimization in quantum computations. As the authors emphasized, the Solovay–Kitaev algorithm is a useful tool for the approximation of arbitrary single-qubit gates for fault-tolerant quantum computation. The authors defined the so-called "search space expansion" approach to modify the initial stage of the algorithm. As the authors found, after some steps the algorithm allows to reduce the requirements of quantum error correction for quantum algorithms in experimental quantum computations.

For a study on the size dependence of the minimum excitation gap in the quantum adiabatic algorithm, see [308]. On the problem of quantum adiabatic optimization algorithm and local minima, see [309]. On the problem of sampling from the thermal quantum Gibbs state and evaluating partition functions with a quantum computer, see [310]. On the problem of the first-order phase transition in the quantum adiabatic algorithm, see [311]. About the problems of adiabatic condition and the quantum hitting time of Markov chains, see [312]. A method of sequential quantum mixing for slowly evolving Markov chains can be found in [313]. For the description of a quantum–quantum metropolis algorithm, see [314]. On the properties of a quantum adiabatic evolution algorithm applied to random instances of an NP-complete problem, see [315]. About the performance of the quantum adiabatic algorithm on random instances of two optimization problems on regular hypergraphs, see [316].

For a study about training a binary classifier with the quantum adiabatic algorithm, see [203]. About the problem of training a large scale classifier with the quantum adiabatic algorithm, see [202]. For a practical demonstration of binary classification using hardware implementation of quantum annealing, see [317]. About the problem of large scale classifier training with adiabatic quantum optimization, see [204]. On the subject of robust classification with adiabatic quantum optimization, see [318].

5.5. Related work

An experimental realization of Shor's quantum factoring algorithm via nuclear magnetic resonance has been demonstrated in [319]. About the implementation of the Deutsch–Jozsa algorithm on an ion-trap quantum computer, see [320]. On the problem of pattern recognition on a quantum computer, we suggest [321]. For a study on predicting crystal structures with data mining of quantum calculations, see [322]. About quantum optimally controlled transition landscapes, see [323]. About the demonstration of two-qubit algorithms with a superconducting quantum processor, we suggest [4]. A quantum algorithm for preparing thermal Gibbs states-detailed analysis can be found in [324]. For a survey on quantum machine learning, see [2]. For a review on quantum learning theory, we suggest [325]. For a review on quantum machine learning and quantum artificial intelligence, see [326]. The principles of quantum artificial intelligence are greatly summarized in [327]. On quantum learning by measurement and feedback, see [157]. On the problem of improved lower bound on query complexity for some quantum learning problems, see [328]. On a study about quantum learning algorithms for quantum measurements, see [155]. For a study on quantum adiabatic machine learning, see [329]. For an optimal quantum algorithm for the oracle identification problem, see [330].

On the subject of quantum deep learning, see [331]. For an introduction to quantum machine learning, see also [332]. The method of fidelity-based probabilistic quantum learning for control of quantum systems is studied in [333]. In [334], the problem of human-level control through deep reinforcement learning is studied. For a study on the experimental realization of a quantum support vector machine, see [335]. In [336], the method of entanglement-based machine learning on a quantum computer is studied. On some advances in quantum machine learning, see [337]. In [338], the problem of quantum learning in a noisy environment is studied. In [339], the problem of quantum gate learning in qubit networks is studied. The problem of quantum inspired training for Boltzmann machines is discussed in [340]. On the problem of tomography and generative data modeling via quantum Boltzmann training, see [341]. About the challenges of physical implementations of RBMs (restricted Boltzmann machines), see [342]. About the role of evolutionary algorithms for hard quantum control, see [343]. For a quantum algorithm for association rules mining, see [344]. For a comparison of classical and quantum machine learning, see [345]. The field of quantum machine learning is reviewed from a classical perspective in [346]. On the connection of deep learning and quantum entanglement, see [347]. For a discussion on the transformation of the Bell-inequalities into state classifiers with machine learning, see [106]. For further analysis on the opportunities and challenges of quantum machine learning in near-term quantum computers, see [348]. On the problem of separability-entanglement classifier, see [349].

For a discussion of quantum dot neural networks, see [132]. In [270], a review on the characterization of the quantum Internet is given. The paper reviews the physical aspects of quantum networking, quantum connectivity, and the physical-layer optical interactions of single photons and atoms. On the problem of exponential separation of quantum and classical one-way communication complexity, see [350]. For a study on parallel photonic information processing at gigabyte per second data rates using transient states, see [351]. The problem of quantum inference on Bayesian networks is studied in [352]. On the solution of the quantum many-body problem with artificial neural networks, see [353]. For a quantum generalization of feedforward neural networks, see [354].

For a study on the equivalences and separations between quantum and classical learnability, see [355]. For a study on quantum algorithms for some hidden shift problems, see [356]. About the problem of polynomial quantum algorithm for approximating the Jones polynomial, see [357]. On the problem of quantum simulations of classical annealing processes, see [358]. For a discrete-query quantum algorithm for NAND trees, see [359]. For the characterization of a quantum algorithm for approximating partition functions, see [360]. For a discussion on super-polynomial quantum speed-ups for boolean evaluation trees with hidden structure, see [361].

In [362], the properties of a preconditioned quantum linear system algorithm are discussed. For the study on quantum linear systems algorithm with exponentially improved dependence on precision, see [363]. On the problem of quantum mixing of Markov chains for special distributions, see [364]. For Scott Aaronson's note on the actual challenges of quantum information processing, see [200]. The problem of prediction by linear regression on a quantum computer is discussed in [304]. In [365], the authors defined a quantum linear system algorithm for dense matrices, and analyzed the complexity of the algorithm. On the problem of estimation of effective temperatures in quantum annealers, see [297]. In [366], the problem of high-dimensional global optimization for noisy quantum dynamics is studied. On the problem of quantum secret sharing, see [367]. For a discussion on fast quantum Byzantine agreement, see [368]. For a study on experimental quantum private queries with linear optics, see [369]. On the problem of quantum communication complexity of establishing a shared reference frame, see [370]. On the problem of reference frames, superselection rules, see [371]. On the problem of spatial reference frame agreement in quantum networks, see [372]. In [115], a method for chip-based quantum key distribution is defined.

A method for quantum clock synchronization based on shared prior entanglement is detailed in [373]. In [374], a quantum algorithm for distributed clock synchronization is defined. A quantum-enhanced positioning and clock synchronization method has been discussed in [375]. The problem of entangled quantum clocks for measuring proper-time difference is discussed in [158]. An efficient algorithm for optimizing adaptive quantum metrology processes is defined in [376]. On the problem of differential evolution for many-particle adaptive quantum metrology, see [377]. For the description of the quantum generative adversarial learning method, see [378]. A scheme on the classification with gate-model quantum neural networks can be found in [379].

6. Conclusions

Here we reviewed the most recent papers and research directions on quantum computing technology. We listed the building blocks of quantum computers, the conditions of the development of large-scale quantum computers, and the most recent research results on the physical implementation of quantum devices, computers, and algorithms. We also addressed some open problems of the field. The results are encouraging, and the conclusion of this paper is positive. Quantum information processing, by exploiting the fundamental nature of information, opens new possibilities in computing, networking, and communications. Quantum computing technologies continue to hold tremendous potential for future computations and communications.

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