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FUNDAMENTALS

Quantum computing

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Abstract
Quantum computing promises to be the next disruptive technology, with numerous possible applications and implications for organizations and markets. Quantum computers exploit principles of quantum mechanics, such as superposition and entanglement, to represent data and perform operations on them. Both of these principles enable quantum computers to solve very specific, complex problems significantly faster than standard computers. Against this backdrop, this fundamental gives a brief overview of the three layers of a quantum computer: hardware, system software, and application layer. Furthermore, we introduce potential application areas of quantum computing and possible research directions for the field of information systems.

Keywords Quantum computing · Quantum physics · Cloud computing · Emerging technology · Information systems

JEL Classification O14 · O32

Introduction

Quantum computing promises to be the next disruptive technology, with numerous possible applications and implications for organizations and markets. A recently published report by McKinsey estimates the global market value of quantum computing to be at USD 1 trillion by 2035, mainly in the financial, chemical, pharmaceutical, and automotive sectors (Hazan et al., 2020). Today, the world's largest technology companies, such as Google, IBM, Microsoft, Amazon, and Alibaba, are already investing billions in research and development of their quantum computing and provide partial access to these quantum computers to the public via cloud infrastructures. However, not only industry players invest but also governments, for example, China is investing USD 10 billion in a national quantum computing laboratory, the U.S. government provided USD 1 billion, and the EU has a budget of overall more than EUR 1 billion (Castelvecchi, 2018; Deicker & Yasiejko, 2018).

Quantum computers exploit principles of quantum mechanics, such as superposition and entanglement, to represent data and perform operations on them (Ding & Chong, 2020). Both of these principles enable quantum computers to solve very specific, complex problems significantly faster than standard computers. Additionally, interference plays

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an important role specifically when reading information from the quantum computer (Aaronson, 2008). Quantum computers can calculate and test extensive combinations of hypotheses simultaneously instead of sequentially (S.-S. Li et al., 2001). Furthermore, some quantum algorithms can be designed in a way that they can solve problems in much fewer steps than their classical counterparts (their complexity is lower). For this reason, quantum computing could represent a significant breakthrough in modern IT in the next few years and might initiate the transition to the "5th industrial revolution" (Hadda & Schinasi-Halet, 2019).

First experiments show promising results, such as the one done by Google in 2019 in which the company claims to have achieved so-called quantum supremacy (IBM "quantum advantage") (Arute et al., 2019). In an artificial experiment, they were able to demonstrate that a programmable quantum device could solve a problem that a classical computer could not solve in a feasible amount of time. However, the task solved by Google 's quantum computer was custom tailored to the specific quantum hardware used and has no real-world applications. Nevertheless, it was an important proof of concept. Furthermore, in 2020, Chinese scientists claimed to have built a quantum computer that is able to perform specific computations approximately 100 trillion times faster than the world's most advanced supercomputer (Zhong et al., 2020).

Given its current state of development, experts anticipate that quantum computing could provide unprecedented advantages, especially in the areas of optimization, artificial intelligence, and simulation (Langione et al., 2019; Ménard et al., 2020). It is likely that simulations of molecules (for chemical and pharmaceutical industries) will be among the first real-world applications of quantum computers. This is because molecules directly follow the laws of quantum mechanics, so using quantum computers is the most natural way of simulating them. Other industries that could soon benefit include the financial sector, transportation and logistics, the global energy and materials sector but also areas such as meteorology or cybersecurity (Gerbert & Ruess, 2018; Langione et al., 2019; Ménard et al., 2020). However, to date, quantum computing has extensive unsolved challenges in physics and computer science, ranging from hardware architectures and data management to application software and algorithms, which requires fundamental research in all these areas and beyond (Almudever et al., 2017).

To inform information systems (IS) research, this Fundamental provides the fundamental concepts of quantum computing and depicts research opportunities. Therefore, we provide in our second section a brief overview of a quantum computer system and its three layers of a quantum computer: hardware, system software, and application layer. The third section introduces potential application areas of quantum computing.[1] Building upon these and the introduced conceptual layer view on quantum computing, we relate to each layer by detailing potential research opportunities in the context of electronic markets. A whole new ecosystem around quantum computing technology itself is emerging already, provoking questions around the change of (1) business models and process innovation, (2) challenges for IT organizations, or (3) sourcing from start-ups, full-stack providers such as Google, IBM, Microsoft, or Alibaba or individual development.

Quantum computing system

In 1980, Paul Benioff envisioned the concept of a quantum touring machine, i.e., the theoretical concept of a quantum computer (Benioff, 1980). In 1982, Richard Feynman proposed the first practical application of a quantum computer: efficient simulations of quantum systems (Feynman, 1982). In general, a quantum computer can be defined as a universal computing device that stores information in objects called quantum bits (or qubits) and transforms them by exploiting very specific properties from quantum mechanics (Ding & Chong, 2020). The quantum computer performs quantum computing, which is a type of computation that collects the different states of qubits, such as superposition, interference, and entanglement, to perform calculations (Grumbling & Horowitz, 2019). Importantly, quantum computers are not intended to become general purpose computers that operate by themselves. They will be highly specialized devices that can solve specific tasks much faster than classical computing. Operating quantum computers will most certainly require a classical computer for loading input/output data, retrieving results from computations as well as controlling the quantum computer's electronic and internal processes. Thus, quantum computers and classical computers form a quantum computing system that enables quantum computers to perform quantum computing. To depict the different layers of a quantum computing system, we adopt the model of Ding and Chong (2020) for three reasons. First, it allows us to analytically distinguish the key components of a quantum component system to illustrate the fundamental mechanisms and elements. Second, it builds on an analytics distinction of hardware, system software, and application, which is mirrored in conceptual views on computing architectures, e.g., cloud computing (Infrastructure-as-a-Service,

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[1] The Fundamentals article is built on the extent body of knowledge on quantum computing. For our literature review we broadly searched for the term "quantum computing" in libraries, such as EBSCO, ScienceDirect, IEEE, or the AIS eLibrary in computer science and IS research. Both the application areas as well as the research opportunities are informed by the prevailing themes of 21 conducted interviews with technology and academic experts from well-established Fortune 500 companies and prestigious academic institutions.

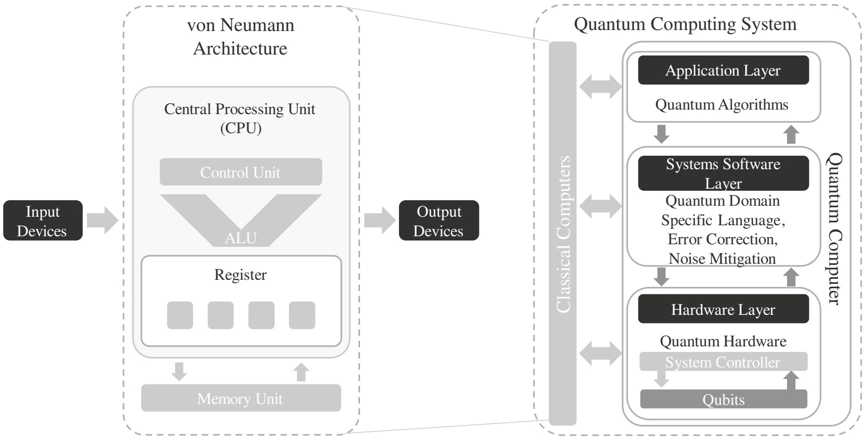

Fig. 1 Showing a classical computer (von Neumann architecture) and a quantum computer forming a quantum computing system (adapted from Ding and Chong (2020))

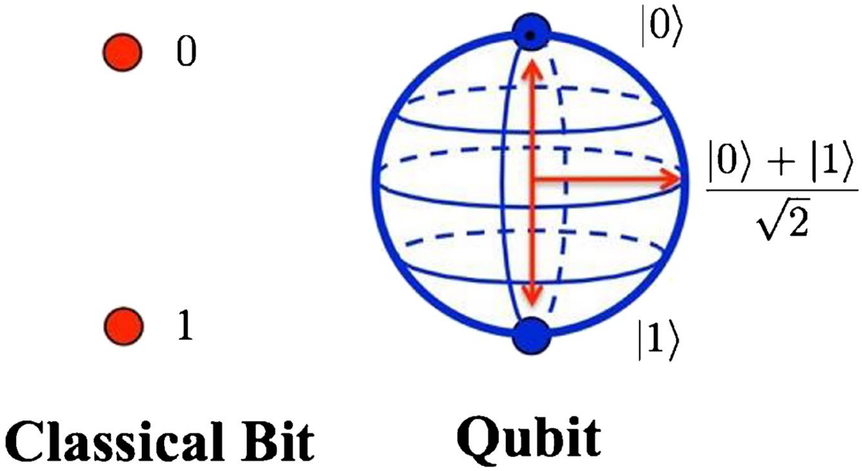

Fig. 2 Classical bit and qubit (Superposition)

Platform-as-a-Service, and Software-as-a-Service) or the layered modular architecture of digital technologies (Yoo et al., 2010). Third, our expert informants distinguished between similar layers as well in their interview statements to explain the state of the art, the challenges for today's organizations, and the functioning of quantum computing systems. Figure 1 shows a quantum computing system consisting of a van Neumann architecture for classical computing and a quantum computer with its three layers architecture, which we will explain accordingly.

Hardware layer

One fundamental difference between classical and quantum computers is how information is stored. Whereas classical computers use bits, which can have the value of either zero or one, to store information, quantum computers use quantum bits (or qubits), which can hold any linear combination of zero and one simultaneously (Steane, 1998). Qubits leverage the advantage of the properties of quantum mechanics and in particular the effect of superposition (visualization see Fig. 2).

Superposition Loosely speaking, a qubit is described by its probability of being either zero or one and not by the distinct value of zero or one. Thus, a qubit can have the probability of being 60% zero and 40% one. Importantly, only at the point of measuring the state of the qubit, it "collapses" to the single classical defined value of either zero or one (Bosch, 2020; Ding & Chong, 2020). The property of superposition has the advantage that a quantum computer with just four qubits is able to represent 16 four-digit numbers simultaneously. With each further qubit, the number of representable states doubles whereas a classical computer, with a sequence of four bits, can only represent a single four-digit number.

The real advantage of quantum computing relies on the fact that one can perform an exponential amount of calculations at the same time. Even though at the end of every program it is possible to read only the solution to one calculation, it is possible to develop a quantum algorithm that makes it very likely that the final result is precisely the one that one is looking for. For example, we might be trying to find out if there exists any possible rarely occurring turbulence that could cause a plane to crash. Instead of simulating billions of combinations of air conditions on a classical computer and checking their individual results, we could simply test almost all possible air conditions at once on a quantum computer and read out only the result that causes the plane to crash.

Entanglement Not only qubits are unique to quantum computing. Entanglement is also a property of quantum mechanics. Entanglement is when the state of one qubit is dependent on the state of another qubit (Steane, 1998). Thus, when two qubits are entangled, making any kind of flip or rotation on one of the qubits would result in the same change happening to the other qubit (Einstein et al., 1935; Schrödinger, 1935). Furthermore, when the state of either one of the two qubits is measured, the state of both qubits collapses to either one or zero (depending on their probabilities). This is even the case when the qubits are far away from each other. Thus, the advantage of entanglement is that when a qubit influences the other qubits around it, all are working in tandem to arrive at a solution. Therefore, qubits can be correlated in a way that is not possible for bits in traditional computers. This opens up new possibilities and gives the quantum computer the ability to process information in a fundamentally different way than a classical computer (Mooney et al., 2019). One example is superdense coding, which is the process of transporting two classical bits of information using one entangled qubit (A. Harrow et al., 2004). This process is especially interesting for secure quantum key distribution (Bennett & Brassard, 2014). This is a secure communication method that implements a cryptographic protocol relying on quantum entanglement and other quantum phenomena. It enables two parties to produce a shared random secret key (entangled qubit) known only to them, which can then be used to encrypt and decrypt messages (Scarani et al., 2009).

Based on the fundamentals of quantum mechanics, we now discuss the approaches to physically represent and manipulate qubits. Broadly speaking, the approaches can be split into two main categories: a) analog quantum computing and b) digital gate-based quantum computing (Ding & Chong, 2020).

Analog quantum computing In analog quantum computing, the quantum state is smoothly changed by quantum operations such that the information encoded in the final system corresponds to the desired answer with high probability. One example of analog quantum computing is adiabatic quantum computers (Albash & Lidar, 2018), which refer to the idea of building a type of universal quantum computing. A special form of adiabatic quantum computers is quantum annealing, which is a framework that incorporates algorithms and hardware designed to solve computational problems via quantum evolution towards the ground states (Vinci & Lidar, 2017). Quantum annealing takes advantage of the fact that physical systems strive towards the state with the lowest energy, e.g., hot things cool down over time or objects roll downhill. As such, in quantum annealing the energetically most favorable state then corresponds to the solution of the optimization problem (Albash & Lidar, 2018). Using the property of superposition, the quantum annealer is able to calculate all potential solutions at the same time, which speeds up the calculation process drastically in comparison to classical computers (Shin et al., 2014). Quantum annealing is most suitable for optimization problems or probabilistic sampling and is used by companies such as D-Wave. However, to date, it is unclear whether the quantum annealing technique will ever achieve significant quantum speedup (Albash & Lidar, 2018).

Digital gate-based quantum computing In digital gate-based quantum computing, the information encoded in qubits is manipulated through digital gates. In comparison to the analog approach in which you sample the natural evolution of quantum states to find the optimal state of low energy, in digital gate-based quantum computers the evolution of the quantum states is manipulated in terms of activity and controlled to find the optimal solution (Ding & Chong, 2020). Thus, the state of qubits is actively manipulated and therefore provides the advantage of being much more flexible, and it can be used to solve large classes of problems, in contrast to quantum annealing. Digital gate-based quantum computing is conceptually very similar to classical computation (Grumbling & Horowitz, 2019). A classical algorithm is run on a computer as a series of instructions (gates such as AND, OR, NOT, …). They manipulate individual or pairs of classical bits and flip them between zero and one states according to a set of rules. Quantum gates operate directly on one or multiple qubits by rotating and shifting them between different superpositions of the zero and one states as well as different entangled states. Companies using digital gate-based quantum computing are, for example, IBM, Google and Rigetti.

System software layer

The system software layer builds on top of the hardware layer and orchestrates the system's processes to leverage the potentials of the qubits (superposition and entanglement). This layer has to cope with challenges of the thermodynamically unstable quantum states. It actively reduces thermal noise within and around the quantum system and performs error correction procedures.

In quantum computing there are many potential sources that can cause noise. For example, quantum computers and especially digital gate-based ones are highly sensitive to changes in the environment, such as vibration, temperature fluctuations, etc. Noise can also be caused by imprecise control of the quantum hardware or manufacturing defects (Ding & Chong, 2020). Most quantum computers even require their chips to be cooled down to a hundredth of a degree above absolute zero temperature to operate. Thus, since noise cannot be avoided, the first era of quantum computers is also called noisy Intermediate-Scale Quantum Computer (NISQ, Preskill, 2018). This abbreviation implies that current quantum hardware using dozens of qubits has error rates that are too high, which need to be improved before we can build useful quantum computers with hundreds, or even thousands, of usable qubits.

Noise in the environment can lead to qubit decoherence which is environmental influences causing quantum states to randomly change (Grumbling & Horowitz, 2019). This is problematic, as a single error in a calculation usually causes the result to be incorrect, unless the error is corrected during the calculation. Since it is impossible to prevent every kind of noise, error correction is important. Ongoing research on quantum error correction seeks to achieve system-level fault tolerance. Quantum error correction differentiates between physical and logical qubits. Logical qubits are represented by a group of physical qubits, which are needed for error correction. Physical qubits work together on correcting errors on individual physical qubits. A group of physical qubits is less likely to cause an error in a calculation than just one physical qubit. Unfortunately, error-correcting mechanisms can cause errors themselves. Depending on the error-correcting mechanism, the relation is typically five to nine physical qubits to achieve one almost error-free logical qubit (Marinescu & Marinescu, 2012; Shor, 1995).

One way to do this is by representing every qubit with groups of several physical qubits that, loosely speaking, work together on correcting errors on individual physical qubits. A perfect physical qubit can work as a logical qubit, as it requires no error correction. Today, the biggest challenge is scaling up to thousands of qubits. Even though the computational space that can be used for calculations doubles (Ding & Chong, 2020) with the addition of every individual qubit, this advantage presently cannot be exploited in its full capacity due to high error rates. One prominent example for trying to increase the number of qubits is IBM, which states that it wants to achieve over 1,000 qubits by 2023, while currently there are machines with 60–100 available (Gambetta, 2020).

Application layer

One of the main challenges of today's quantum computers is the unsolved problem of efficient quantum memory (Ciliberto et al., 2018). There exist several theoretical proposals for building quantum random access memory (QRAM). Even though it may be experimentally difficult to build (just as the quantum computer itself), recent publications demonstrated several possible paths of doing so (Hann et al., 2019; Park et al., 2019). Thus, currently exists no efficient way to store states of qubits in a memory for a long time for other calculations. Therefore, data needs to be loaded from a classical computer to the targeted quantum computer, and after performing the calculation states need to be read (measured) by the classical computer before the qubits lose their information. Due to the no cloning theorem, we are also not able to make copies of quantum states and use them for calculations. The only way to load a quantum state from quantum memory into a quantum program is by applying a SWAP operation, and thereby removing it from the memory.

When a quantum state is measured, it collapses to either one or zero. Therefore, we have no way of finding out what state a certain qubit is in. The only way we can approximately find out what state a qubit is in is if we have multiple copies of the same qubit and measure them all. In some cases, reading the classical data may dominate the cost of quantum algorithms so that it cannot speed up the whole algorithm at the macro level. Reading out the data exactly may be infeasible, which cannot meet the computing needs in some tasks. This is especially the case for methods that need large data sets, such as machine learning and artificial intelligence.

Finding a useful algorithm for quantum computers is mostly about constructing it in such a way that the probability of measuring the desired outcome is maximized. Even though the output of the quantum computer may be an exponentially large number of solutions, we are usually just interested in a small subset of these solutions. Finding them without having to run the whole algorithm many times is the art of quantum algorithm construction. Here are three of the most important quantum algorithms.

- **Grover's algorithm** is also known as the quantum search algorithm. Grover's algorithm is used for searching an unstructured database or an unordered list. Classically, for finding a particular item in a database of size N, we need to go through, on average, N/2 items to find the right one. Using Grover's algorithm, we can do this in only $\sqrt{N}$ steps, on average. For a large N, this can be remarkably faster. This is called a quadratic speedup (Grover, 1996).
- **Shor's algorithm**, also known as the integer factorization algorithm, can factorize integers almost exponentially faster than the fastest known classical algorithm. Factorizing integers is very difficult computationally and is therefore also the basis of RSA encryption (Shor, 1994).
- **HHL (Harrow Hassidim Lloyd)** is also known as the quantum algorithm for linear systems of equations. The algorithm can estimate the result of a function of

the solution x of a linear system ($Ax = b$), where A is a matrix and b a vector (A. W. Harrow et al., 2009).

Application areas of quantum computing

Thanks to the enormous progress in hardware, more and more established commercial companies are investing in quantum technology. Examples include Boehringer Ingelheim, who recently announced a research partnership with Google (Boehringer-ingelheim, 2021), and Daimler, who announced progress in the field of materials research (Motta et al., 2020), or chemistry giants like BASF who aim to stay at the forefront of chemistry research and business (Hartmann & Deppe, 2021). Quantum computing has three essential capabilities to address today's computational problems that current computers are not or only partially capable of and that bear benefits for companies: 1) search and graph, 2) algebraic and 3) simulation (Hoffmann, 2021; Li et al., 2020). These capabilities determine the potential applications of this technology in numerous industries, such as finance, chemistry and pharma, manufacturing, energy, or cybersecurity (Gerbert & Ruess, 2018; Langione et al., 2019; Ménard et al., 2020). Table 1 provides a summary of the problem types, approaches and potential use cases.

Search and graph

The fact that a qubit can theoretically represent an infinite number of states allows for solving complex combinatorial optimization problems, which is currently one of the major application areas for current quantum computing technologies, such as the solution of D-Wave (Johnson et al., 2011). Combinatorial optimization is the process of finding one or more optimal solutions to a problem. Examples of such problems include supply chain optimization, optimizing public transportation schedules and routes, package deliveries, etc. These solutions are searched for in a discrete (finite) but very large configuration space (i.e., a set of states). The set of possible solutions can be defined with several constraints and the goal is to optimize the objective function with the best solution.

Since the problem spaces in certain complex problems are very large, it is extremely difficult to find the optimal or even a single good solution to these problems with classical computers in a reasonable time frame or with sufficient accuracy. Such combinatorial optimization problems often pose a great challenge for the private as well as the public sector. While they are often simple to describe, they turn out to be very difficult to solve. Combinatorial optimization problems may be divided into order, assignment, grouping, and selection problems, and within these classes, subclasses exist, such as the knapsack or the traveling salesman problem. In addition to the property that there can be a lot of qualitatively different solutions for a problem, no known algorithm exists that can easily compute these problems directly. Searching very large problem spaces requires an enormous amount of computing capacity and time.

Respectively, quantum computers are expected to play a decisive role in the financial services industry. Especially players specializing in portfolio optimization and arbitrage could benefit (Egger et al., 2020). From a very large pool of existing financial instruments, a subset should be selected so that a certain portfolio volume is achieved, while at the same time a large number of factors must be taken into account to minimize risk and achieve profitability (Chakrabarti et al., 2021). Further, Deutsche Börse (a German company offering marketplace organizing for the trading of shares) already experimented with the applicability of quantum computing for a sensitivity analysis on one of their risk models, a computation that is too expensive

Table 1 Overview quantum computing problem types, approaches, and potential use-cases

Problem type	Approach	Example use-cases
Search and graph	Finding one or more optimal solution(s) to a complex problem. Often the problems involve a large number of possible parameter combinations.	- Find optimal parameter configuration to optimize portfolio in the finance industry - Search for possible routes to optimize traffic flow in transportation - Factorize prime numbers to break encryption in secure communication
Algebraic	Calculating complex network architectures and the weights for machine learning and artificial intelligence. This involves transforming and calculating large matrices.	- Transform matrices to find objects in images in computer vision - Find patterns in texts to understand semantics in natural language processing
Simulation	Calculating how states of a system change through manipulating parameters to analyze the behavior of complex systems.	- Simulate states of molecules and their changes to understand chemical reactions in pharma industry - Simulate the behavior of materials to find more efficient materials in battery industry

to be run on classical computers (Braun et al., 2021). Due to its suitability to solve optimization problems, another application of quantum computing is the optimization of flow, e.g., of traffic or goods. Collaborating with D-Wave Systems, VW has already shown in a pilot project how to optimize a simplified traffic flow in the city of Lisbon by leveraging quantum annealing technologies (Neukart et al., 2017; Yarkoni et al., 2019) – a project that started in late 2016 with a proof-of-concept project. It investigated the readiness of quantum computing by building a traffic-flow optimization program that used GPS coordinates of 418 taxis in Beijing to resolve traffic congestion.

Moreover, quantum computers are superior to classical computers regarding certain prime factorization procedures that play an important role in the secure encryption of data. A popular example for this is the aforementioned Shor (1994) algorithm that factors a number into its prime factors, a process used often in cryptography and cybersecurity. A dataset encrypted with quantum technology would be impossible to decrypt with classical computer technology, or at least not in time periods relevant to human users. Conversely, it would be easy for a quantum computer to crack data encrypted with classical RSA technology – a phenomenon that may be coined as quantum threat (Mone, 2020).

Algebraic

The ability of quantum computing to accelerate optimization problems plays a crucial role for narrow AI approaches (Gao et al., 2018; Langione et al., 2019). Quantum computing can help to calculate complex network architectures and weights for machine learning and artificial intelligence. Quantum computing shows its advantage in transforming and calculating large metrices. For example, in the context of supervised learning, the model aims to minimize the error between the prediction of the model itself compared to the input and adequate output or label given. Quantum computers offer several approaches to solving problems like this, thereby, again, accelerating calculation and allowing for more complex network architectures (DeBenedictis, 2018). They may be applicable to all relevant practices or sub-tasks of artificial intelligence, such as image processing and computer vision (Dendukuri & Luu, 2018) or natural language processing, as demonstrated in an experiment by Cambridge Quantum Computing (Lorenz et al., 2021). Having said that, it is important to note that, so far, no near-term machine learning algorithm with provable speedup has been found.

Simulation

A quantum computer has a fundamental advantage over classical computers: It can simulate other quantum systems (e.g., a nitrogen molecule) much more efficiently than any computer system available today. For classical computers, even molecules with comparatively low complexity represent an almost unsolvable task. In the 1980s, Richard Feynman theoretically substantiated the possibility of a quantum-based computer for simulating molecules (Feynman, 1982). Since then, researchers have attempted to transfer the quantum system of a molecule into another quantum system, i.e., into the quantum computer, in order to simulate it. One new hope in the application of quantum computers is the simulation of more efficient catalysts for ammonia synthesis in the Haber–Bosch process, which today accounts for about 1 to 2 percent of global energy consumption. Better catalysts could reduce energy consumption and thus also help slow global warming. Even quantum computers without full error correction may already be better suited for this application than simulations on classical computers (Budde & Volz, 2019).

Furthermore, the development of active ingredients and drugs is often a lengthy and very cost-intensive process. This is due in particular to the fact that a large number of substances have to be tested on a trial-and-error basis in the real world. Yet, building on the same principles of quantum physics, quantum computing may be able to virtually replicate the behaviors such that simulation-based research may sooner or later replace this cost-intensive process.

For instance, BASF, pursuing its high requirements for the accuracy of quantum chemical calculations, investigated, in collaboration with the company HQS, the applicability of quantum computing. Specifically, they aimed to understand the quantum mechanical calculation of the energy course of chemical reactions, as this actually allows for the prediction of the probable course (i.e., how does the reaction proceed, which products, by-products, etc., are formed, how can I accelerate the reaction with the help of catalysts, etc.) of chemical reactions. This application of needed methods reaches the limits of conventional computing methods (Kühn et al., 2019). In addition, material research on the functioning of batteries is deemed to inform today's electromobility and is already targeted by automotive giants such as VW (Neukart, 2021; Ziegler & Leonhardt, 2019).

Link to the field of information systems

Even though there are high investments in quantum computing, most expert estimations still place the widespread industrial application of quantum computing at least five to ten years in the future. Its exact manifestations in many critical areas remain unclear. Thus, it is the task of today's research community to creatively conjure up and explore the full potential and the socio-technological consequences of quantum computing. Therefore, based on analyzing existing literature and the conducted interviews with 21 leading

Table 2 Further areas of research and potential research questions

Further research and development	Potential research questions
Quantum computing ecosystems as a new networked business	- Does the access to quantum computing need to be regulated? - Does quantum computing need new sourcing strategies? - How does the emerging quantum computing ecosystem act as a spoke component to other industries and ecosystems? - Which transformation may result from the emergence of a quantum computing networked business?
Digital understanding as a foundation for quantum computing use cases and ecosystems	- What approaches could be used or developed to analyze business problems and therefore leverage the potential of quantum computing? How can these problems be described mathematically? - What are possible design principles of artifacts to describe use cases? - How will quantum computing impact the modeling of a social and economic reality as a transformation from binary to multidimensional quantum states?
Quantum computing as a challenge for IT organizations and IT service providers	- What are possible security approaches to protect legacy IT with old encryption standards considering the quantum threat? - Can quantum computers and artificial intelligence be used for real-time threat and anomaly detection? - How can quantum computers be used to simulate possible intrusions and cyber-attacks for calculating risk–cost evaluations?
Quantum computing skills	- How could information systems act in a mediating role for adopting quantum computing technologies? - Should quantum computing be included in the information systems curriculum? - How can future information systems managers be trained to be aware of the disruptive potential of quantum computing? - How can management leverage the potentials of available techniques, approaches, and platforms around quantum computing? - How can gaps of knowledge and access to infrastructures be mitigated?

experts in industry and research, we propose the following four initial directions for research on quantum computing in information systems (for a summary, see Table 2): 1) quantum computing ecosystems as a new networked business, 2) digital understanding as a foundation for use cases and ecosystems, 3) quantum computing as a challenge for IT organizations and IT service providers, and 4) skills needed to leverage quantum computing in the quantum computing field.

All of these directions try to consider the fact that quantum computing despite its disruptive potential will initially be an extension of computing capabilities for established electronic markets, ecosystems, and its participants (see Fig. 3), while new ecosystem participants are already establishing themselves (e.g., IonQ or Rigetti).

We further try to focus on established research areas and the focus of our research community.

Quantum computing ecosystems as a new networked business The adoption and diffusion of quantum computing will heavily rely on an emerging ecosystem comprising technology providers, such as IBM, Google, Microsoft, or Amazon Web Services, start-ups with specific playgrounds such as 1Qbit or IonQ as well as consulting firms and academic institutions to support customers in adopting and building applications using quantum computing technologies (Carrel-Billiard et al., 2021; IBM, 2019). Also, the European Union built their own ecosystem with the "Quantum Flagship".[2] Companies, providers, research institutions, and governments ultimately need to engage in such an ecosystem to allow for getting hold of capabilities that transcend their own organizational boundaries or even their entire industry (e.g., building their own computing infrastructures, translating business problems into mathematical and quantum problems, etc.) (Carrel-Billiard et al., 2021). Due to this emerging new organizing logic and structure for quantum computing, key aspects need to be considered when pursuing information systems research in this context.

First, the entrance barrier to quantum computation is expected to be very high due to multiple limitations such as the necessity of knowledge in quantum physics, the expensiveness of building quantum computers and the shortage of experts in the labor market. As such, they may enforce divides and limit access. Steps should be taken to reduce a possible quantum divide. Second and consequently, incumbents will need to rely on the capabilities that technology providers, start-ups, consulting firms, or academic institutions may provide, as they might go beyond their domain expertise. As such, prevailing networked businesses and ecosystems need to develop methods and technologies to purposefully connect their way of doing digital business with

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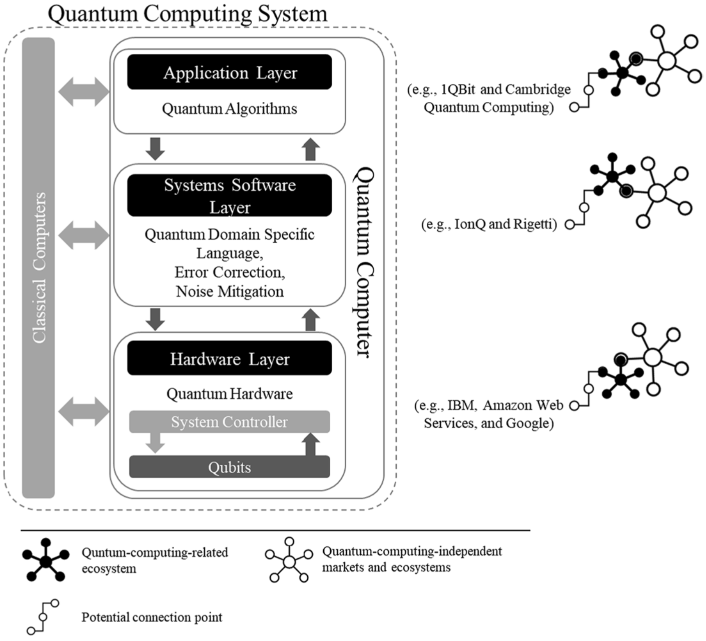

Fig. 3 Quantum computing system and relevant point of contacts for established ecosystems

the emerging quantum computing ecosystem players in the different layers, namely the hardware layer (e.g., Amazon Web Services, IBM, and Google), the system layer (e.g., IonQ and Rigetti), and the application layer (e.g., Cambridge Quantum Computing or 1QBit) (IBM, 2019).

Today, the playground is already diverse, with fuzzy boundaries leading to the need for design-science-oriented guidance for incumbents to assess their own business and technology maturity. For instance, IonQ and Rigetti are positioned on both the hardware and the system software layer. Additionally, for companies it is important to mediate the engagement with different players as part of their quantum computing road map. Thus, possible research questions might include the following: Does the access to quantum computing need to be regulated? Does quantum computing need new sourcing strategies? How does the emerging quantum computing ecosystem act as a spoke component to other industries and ecosystems? Which transformation may result from the emergence of a quantum computing networked business?

Digital understanding and representation as a foundation for quantum computing use cases and ecosystems The proliferation of quantum computing as a generative technology for calculating with an enormous speedup relies on a fundamental premise: The problem which will be solved by a quantum computing approach needs to be replicated in the form of digital data on which basis a calculation becomes possible in the first place. Emerging technologies such as machine learning already challenge today's organizations. The main reason is that it is complicated to digitally represent business practices and economic behavior to allow for analysis. This phenomenon may be summarized as datafication (Lycett, 2013). As such, the dematerialization of the physical world in the form of digital data as a digital representation is an essential prerequisite (Recker et al., 2021). Only with this prerequisite, one may use quantum computing when calculating the physical world based on its datafied digital representation.

Achieving an adequate digital representation of the respective quantum computing problem requires a mathematical and conceptual understanding to allow for assessing, understanding, and realizing the value of quantum computing aside from other computing approaches (e.g., high performance computing). Furthermore, quantum computing may also serve as an enabler for process innovation; for example, it could be interesting for research areas around process mining (Mendling et al., 2020), such as analyzing and optimizing process configurations or simulating contexts of processes or configurations of processes (vom Brocke et al., 2021). Therefore, research on use case analysis and in particular on methods of how to find, describe, and analyze use cases systematically and at scale are highly relevant. Possible research questions could include the following: What approaches could be used or developed to analyze business problems and therefore leverage the potential of quantum computing? How can these problems be described mathematically? What are possible design principles of artifacts to describe use cases? How will QC impact the modeling of a social and economic reality as a transformation from binary to multidimensional quantum states?

Quantum computing as a challenge for IT organizations and IT service providers IT competencies are increasingly built up in business units using commercial IT services without having the IT department in the loop. Quantum computing drives this change even further, since for the next few decades, the first quantum computers will likely only be available via the cloud for most companies (Carrel-Billiard et al., 2021). IT departments are therefore under pressure in terms of how to manage quantum computer usage in companies, especially with regards to transmitting the respective data which is needed for quantum-computing-based calculations. This is of particular interest, since data preparation including data input and output might be the bottleneck for quantum computing in the long run. Furthermore, quantum computing and especially the ability of prime factorization is a threat for current encryption standards and poses huge challenges for the IT organization. Even though new encryption techniques can be used once quantum computers become a real threat to current encryption protocols, past communication and old data can be decrypted retroactively.

Future research questions could include the following: What are possible security approaches to protect legacy IT with old encryption standards? Can quantum computers and AI be used for real-time threat and anomaly detection? How can quantum computers be used to simulate possible intrusions and cyberattacks for calculating risk–cost evaluations? The latter is of special interest due to the hyper-connectivity of digital services, which poses an enormous vulnerability for an infrastructural attack.

Quantum computing skills Historically, the role of information systems has been to bridge the gap between informatics and business. In the age of quantum computing, this role is becoming more important than ever before. In order to leverage the potential of quantum computing, at least three roles are required (Carrel-Billiard et al., 2021; Hughes et al., 2022): First, mathematical and quantum physical skills are needed to translate problems into mathematical formulas. Second, domain expertise is needed to integrate the business problem within the mathematical formulation. Third, an intermediary is needed to facilitate between both roles (Gartner, 2019). Due to the high complexity and high specialization of the job types (e.g., error correction specialist, quantum algorithm developer), the entrance barrier to the field of quantum computing is significantly higher than for regular "coding". Additionally, for years there has been a shortage of STEM (Science Technology Engineering Mathematics) graduates, which may amplify the war for talents in quantum computing (OECD, 2021). Having said that, companies such as IBM, Google, or research institutions such as ETH, are working on developing programming languages and compilers in which a device will decide if the application is suitable for a quantum computer. However, according to experts, this will take years. Future research questions could include the following: How could information systems act in a mediating role for adopting quantum computing technologies? Should quantum computing be included in the information systems curriculum? Since quantum computing knowledge is important on a strategic level, how can future information systems managers be trained to be aware of its potential? How can management leverage the potentials of available techniques, approaches and platforms around quantum computing? How can gaps of knowledge and access to infrastructures be mitigated?

Conclusion

In this Fundamentals article, we provide an overview of the constituting concepts of quantum computing. Against this backdrop, this fundamental gives a brief overview of the three layers of a quantum computer: hardware, system software, and application layer. On this basis and our access to leading experts in quantum computing, we propose several focus areas for studying the socio-technical implications of quantum computing for the emergence of new ecosystems or their extensions as well as for ecosystem participants themselves.

The disruptive nature of quantum computing will lead to various changes in all socio-technical components of organizations and in IS-related ecosystems. As such, we expect a large impact on the IS discipline in academia, practice, and teaching. At the same time, we are aware that quantum computing is in its infancy, both as a field of research for IS research as well as in its development towards an established and well-understood computing approach. Against this backdrop, we hope to inform and inspire research on the socio-technical peculiarities of quantum computing on the ecosystem level or level of electronic markets (e.g., quantum computing ecosystems as a new networked business), the organizational level (e.g., the role of IT organizations and service provider for establishing quantum computing), the individual level (e.g., quantum computing skills) as well as on the crucial role of data (i.e., digital understanding and representation of economic behavior) to allow for quantum computing calculations.

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