Bus Inf Syst Eng 65(4):361–367 (2023)
https://doi.org/10.1007/s12599-023-00823-w

EDITORIAL

Quantum Computing

Michael Nofer · Kevin Bauer · Oliver Hinz · Wil van der Aalst · Christof Weinhardt

Published online: 17 July 2023

1 Introduction

There are signs that we are approaching a technical revolution that might take humankind's computational capabilities to a new level. Quantum Computing leverages the principles of quantum mechanics, enabling the computational power to solve specific problems currently intractable for classical computers (e.g., cracking cryptographic keys). Since we are getting to a point where we can no longer build smaller, more powerful, more efficient devices with conventional methodologies, we need to think of new ways for technological progress. The manufacturing of microchips is reaching its limits in the use of traditional architectures. Hence, new and more advanced technologies need to address the challenges of increasing energy consumption and data processing. Connectivity, scalable architectures and concepts like Cloud Computing and Software-as-a-Service have already helped to scale computational-intense applications in the last years and have attracted the interest of IS researchers (e.g., Benlian et al. 2009; Benlian et al. 2018; Messerschmidt and Hinz 2013). Looking ahead to the next generation, computing will comprise technologies that enable high-performance applications far beyond today's possibilities. One prominent example with a disruptive potential is Quantum Computing. While there are abundant open questions and directions for further developments, researchers in this area have made substantial progress in the last decade, indicating that, after medical imaging, lasers, and superconductors, another quantum-technological innovation might be approaching. We, therefore, intend to provide an overview of the current state of Quantum Computing research and outline how this new technology might stimulate research in Information Systems.

Even though the term computing may suggest that quantum computing is simply a considerably improved version of current computing devices, this is far from being the case. Just as light traditional computers are not just substantially improved mechanical typewriters, quantum computing is a completely new technology, whose difference from traditional computers and potential implications for business and socio-economic processes could be considerable. The idea for quantum computers was born in the 1980s. Richard Feynman envisioned a quantum device that follows the laws of quantum physics (Feynman 1982). Quantum computing performs computations exploiting the behavior of quantum particles (Shor 1998), especially related to the phenomenon of the wave-particle duality. While the elementary units of information storage and processing in classical computers are bits, which can be in one of the two mutually orthogonal states $|0\rangle$ or $|1\rangle$, their mechanical analogs in quantum computing are quantum

M. Nofer · O. Hinz (✉)
Goethe University Frankfurt, 60323 Frankfurt am Main, Germany
e-mail: ohinz@wiwi.uni-frankfurt.de

M. Nofer
e-mail: michael.nofer@gmail.com

K. Bauer
University of Mannheim, 68161 Mannheim, Germany
e-mail: kevin.bauer@uni-mannheim.de

W. van der Aalst
RWTH Aachen, 52056 Aachen, Germany
e-mail: wvdaalst@pads.rwth-aachen.de

C. Weinhardt
Karlsruhe Institute of Technology (KIT), 76133 Karlsruhe, Germany
e-mail: weinhardt@kit.edu

bits (qubits). Just as with traditional bits, qubits can be manipulated using logical gates, which, however, differ from traditional gates in certain aspects. The building blocks in classical computing are logic gates that perform Boolean logic, i.e., operators such as AND, OR, NOT. In quantum computing, information is not manipulated using Boolean operations. Quantum logic gates operate on the states of a set of qubits that are probabilistic.

The potential supremacy of quantum over traditional computing stems from the laws of quantum mechanics. A qubit's property can be in one of the basic states $|0\rangle$ or $|1\rangle$, and additionally be in a linear combination of both states (Fig. 1). This additional state is referred to as the superposition $|\psi\rangle = a_0|0\rangle + a_1|1\rangle$ where a_0 and a_1 are called probability amplitudes and can be complex numbers satisfying the condition $|a_0|^2+|a_1|^2= 1$. Formally, we can thus think of the state of a qubit as a unit vector in a two-dimensional complex vector space. A superposition allows qubits to be in multiple states simultaneously (DiCarlo et al. 2009).

It is impossible to identify the exact superposition of a qubit. That is, whenever we try to measure the exact values of a and b, the qubit collapses to one of the two basic states $|0\rangle$ or $|1\rangle$ respectively with probability $|a_0|^2$and $|a_1|^2$. For example, a qubit in superposition $a_0 = a_1 =$ Sqrt(0.5) will be in state $|0\rangle$ or $|1\rangle$ with an equal probability 0.5 when measured.

A system of qubits possesses another quantum–mechanical property that derives from superposition and the probabilistic collapse to basic states under measurement. This property is called entanglement. It describes that the measurement outcomes of qubits can correlate, i.e., are not independent. For instance, if we measure the state of one qubit in a two-qubit network system and it collapses to the basic state $|0\rangle$, , then the entangled qubit's state immediately collapses to $|0\rangle$, yielding the system's overall state of $|00\rangle$. . Due to entanglement, any operation performed on one of the qubits can be instantaneously reflected in the other. This relation between entangled qubits remains active over arbitrarily large distances (see for example China's Micius Quantum Satellite Experiments, Popkin 2017). Building networks of remote entangled qubits promises a wide range of applications including a quantum Internet (Pompili et al. 2021).

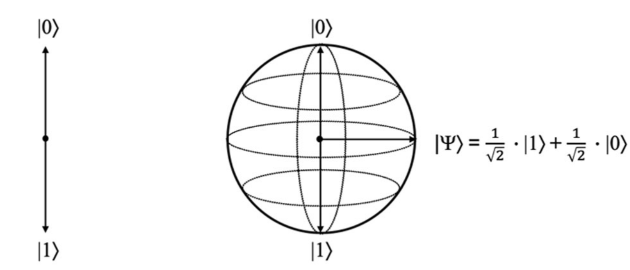

Fig. 1 Illustration of a classical bit and a qubit

Together superposition and entanglement are the basis of quantum parallelism, the fundamental quantum–mechanical property enabling the simultaneous evaluation of mathematical functions $f(x_1,\ldots,x_n)$ of all their inputs $x_1,\ldots,x_n$ using a single quantum circuit (in combination with logical quantum gates). This behavior is completely different from classical parallel computing where multiple Boolean circuits can only evaluate parts of the input at the same time. Due to this property, it is possible to run *f(.)* simultaneously for more than one input allowing us to determine global properties of *f(.)*. This effectively permits an exponentially faster solution of certain problems in comparison to traditional computers. However, one must distinguish between performing such parallel computations and reading out the value of the functions of all inputs. In fact, only one value of *f(.)* can be retrieved in one iteration since all other values are inaccessible. In contrast to classical bits, we cannot determine the state of a qubit simply by reading. We need to *measure* and the result depends on the above-mentioned probability amplitudes a_0 and a_1 that can take on negative or complex values. Thus, in contrast to classical probabilities, probability amplitudes are allowed to be negative which can lead to constructive interference (both are negative or positive) or deconstructive interference (one is positive and one is negative). While quantum computers are faster than traditional computers in performing multiple simulations, they hardly produce one correct answer to a question in a single run. Instead, quantum computing delivers probability distributions that we can understand as a range of results over multiple runs, which is the reason why quantum computers will not entirely replace classical computers. If the input is large or the output is large, e.g., event logs with billions of events in process mining applications, then it is probably infeasible to use quantum computing. However, they provide distinct benefits when solving very specific and complex problems, such as simulation or optimization tasks, where excluding a large fraction of possibilities is timesaving and efficient. It makes sense that the practical application of such quantum algorithms on working and scalable quantum computers offers a wealth of possibilities that human society at the macroscale, and organizations at the microscale, might benefit from (Trabesinger 2017).

2 Status of Quantum Computing

Quantum Mechanics is a relatively young field of science established around the early 1930s. Therefore, it is not surprising that the application of this field's insights in the form of quantum-based technologies is far from being fully developed, especially when it comes to quantum computers. There are some challenges that researchers still need to overcome before humankind can tap the full potential of the commercial scale-up of quantum computers.

Quantum decoherence, sometimes also referred to as quantum noise, is the process of interaction between the quantum system and the environment, leading to the loss of quantum information (Shor 1996). Changing electric fields, temperature fluctuations, vibrations, or other external influences can cause this disturbance (Lidar et al. 1998). We can also observe similar effects of interactions with the environment in classical physics. For instance, mechanical energy is converted to heat when rubbing your hands. Unfortunately, quantum states are extremely sensitive to noise. Whenever a quantum system is not perfectly isolated from its environment, decoherence is almost guaranteed, corrupting quantum information and causing errors in the system's evolution. As quantum computers work through manipulating quantum information stored in superpositions, the loss of quantum information, or the introduction of imprecisions can lead to substantial errors in computations. Put differently, while imperfections are inevitable in information processing tasks (e.g., bit-flip errors in traditional computers), quantum computers are particularly prone to exhibit errors, making them more vulnerable than classical computers.

To solve this issue, some of the current quantum systems operate at extremely low temperatures where particle movement is restricted and qubits remain longer coherent. Another way to tackle decoherence problems is the development of quantum error-correction techniques that enable fault-tolerant quantum computing (Shor 1996). Developing error-correction methods is particularly challenging because the required measurement of errors in the quantum state usually leads to the destruction of quantum information, such that approximated measurements of indirect syndromes of errors are required. Quantum computers' vulnerability to imprecisions and errors typically increases with the number and duration of operations performed on the qubits so that the scaling of computational performance in a system makes it increasingly difficult to maintain low error rates. Researchers and practitioners agree that the ability to detect and deal with quantum errors in a resource-efficient and scalable way is one of the next key steps toward a universal quantum computer. Current limitations in quantum computing result less from an inability to build large qubit systems than from the inability to correct the increasing number of resulting quantum errors associated with systems that are more complex. Hence, academia and industry devote their efforts to developing frameworks for quantum error detection and correction.

Appropriate error-correction systems could lead to considerable advances concerning the broader application of the Noisy Intermediate-Scale Quantum Devices (NISQ), without having to wait for fault-tolerant devices. Preskill (2018) introduced "NISQ" as a term to summarize today's leading quantum systems, which are far away from fault-tolerant quantum computing. They build upon a two to three-digit number of qubits and already showcase noteworthy successes demonstrating the viability of these approaches. In retrospect, the late 2010s have been encouraging years for scientists and practitioners advocating quantum computing. Researchers and companies have developed an increasing number of devices that deliver proofs-of-concept for the practical application of quantum hardware (see for example Almudever et al. 2020). However, research does not only push ahead concerning the production of quantum hardware. The development of applicable quantum software that can run on these quantum machines, enabling quantum advantage, sees progress as well. On today's simulators, it is already possible to test typical mathematical models for their feasibility for large-scale quantum computers.

A growing body of research on quantum algorithms provides experimental proofs-of-concept demonstrating that these algorithms are ready to run on more sophisticated quantum devices in the future. A very promising example is Shor's algorithm for rapid prime factorization of large integers (Shor 1994). While there still exist technical challenges, especially related to quantum-errors, first experiments show successes in the scalable implementation of the algorithm on qubit systems (see for example Monz et al. 2016). The presumed security associated with Rivest-Shamir-Adleman (RSA) encryptions rests on the knowledge that the factorization of large integers using standard computers is an intractable problem (Rivest et al. 1978). Applying Shor's quantum algorithm on a sufficiently powerful quantum computer, however, can considerably facilitate breaking esp. asymmetric encryptions. The algorithm on a powerful quantum computer would thus render conventional encryption insecure and would make many applications like online banking as it is secured now vulnerable to successful attacks. Another example, particularly interesting for Information Systems researchers, is the development of a quantum-based recommendation algorithm that efficiently samples from an approximated preference matrix (Kerenidis and Prakash 2016).

Quantum systems can be build using different technologies, which have their own benefits and challenges. Although other methodologies are also subject to exploration (e.g., topological qubits), the most widely used technologies and therefore most promising candidates for scalable quantum computers are superconductors, trapped ions and photons.

Superconducting electronic circuits are the predominant approach among the leading technology giants, such as IBM, Google and Intel (e.g. Arute et al. 2019). Unlike photons, atoms or ions, superconducting circuits are not microscopic but macroscopic systems leveraging two robust properties: (i) Superconductivity is the phenomenon of zero electrical resistance in certain materials at very low temperatures and (ii) The Josephson effect can be observed when two superconductors are coupled through an insulator. It produces a current without any voltage flowing across this Josephson Junction, which activates the nonlinearity necessary for constructing superconducting qubits.

Trapped ion quantum technology uses charged atoms as qubits. Their basis states $|0\rangle$ and $|1\rangle$ can be encoded with their electronic energy levels. Among others, hyperfine and optical qubits are most widely used (Humble et al. 2019). Quantum logical operations on the ions can be achieved by laser beams. The isolation of the qubits from the environment works well due to the vacuum conditions in the trap. While these qubits are very stable and produce low error rates, the realization of scaled solutions is still a major challenge (e.g., Ballance et al. 2016).

Photons are another approach to building quantum computers, i.e., particles of light, which are rather isolated from the environment and therefore less prone to decoherence. This property allows the realization of long quantum states over long distances. Moreover, photons have multiple degrees of freedom, such that the highly scalable encoding of quantum information is feasible (Flamini et al. 2018). Quantum systems harnessing photons can be cooled using laser techniques. Due to their robustness and mobility, photons are best suited for transmitting quantum information in a very fast way. One major drawback is that photons seldom interact with each other. Multi-photon entanglement therefore becomes rather challenging although scientists have reported several approaches to entanglement generation during the last decade (e.g., Hamel et al. 2014).

3 An Agenda for Information Systems Research around Quantum Computing

The above-mentioned advances in the field of quantum computing are poised to entail substantial technological improvements in a wide variety of domains where traditional computing systems currently fail. We observe an increasing number of incremental discoveries in the field of quantum computing. Considering the history of traditional computing in the last decades, we see that the availability of increasingly powerful hardware has always accelerated the development of innovative algorithms and further applications that we were not able to imagine before. The advances in quantum computing coincide with significant innovations in classical computing (e.g., cloud computing, high-performance computing) and Artificial Intelligence. Taken together, these areas complement and stimulate each other, which might lead to completely new workflows accelerating the already evolving transformation process in business computing. One example of a manifestation of this trinity is the access to quantum systems through the cloud. In contrast to the beginning of many previous technological revolutions when new resources were a rare privilege, almost everyone has the chance to leverage quantum computing by now. While today's research focuses on developing different quantum applications, such as simulation, optimization or machine learning, the possibilities in two decades might lie beyond our power of imagination. Computer scientists in the 1980s were also not aware of smartphones, which have changed the way we live. Therefore, it is hard to predict all the areas that quantum computing might affect in the future.

There are still considerable technical obstacles that scientists need to overcome to realize a full-scale, fault-tolerant quantum computer. However, current advances suggest that the achievement of quantum supremacy, or at least quantum advantage in specialized domains, is increasingly in reach. While such specialized technical advances can potentially lead to unforeseen gains in human welfare, e.g., the development of highly effective cancer treatment, and spur further technological innovations in the field, many important questions concerning quantum computing remain. Especially with regard to socio-technological requirements for and consequences of the employment of quantum devices, we know fairly little as of today. Insights in this area are indispensable to tap the full potential of this technology, e.g., increase our understanding of the determinants for the adoption by human users.

The field of Information Systems has a special responsibility here. With its interdisciplinary focus, the discipline is predestined to advance the knowledge about how quantum computing technologies interact with socio-technological systems on different levels. To this end, Information Systems researchers need to become quantum-ready and grapple with the foundations of this technology in more depth. By doing so they will lay the groundwork to establish the new and necessary research in Information Systems that examines the potential and actual effect of quantum computing. As a new field of inquiry, there are abundant avenues of future research that researchers can follow up. In the following, we conclude with the provision of a brief and by no means exhaustive outlook on urgent questions that will crucially contribute to the adoption and diffusion of quantum computing (Table 1). Our research

Table 1 Potential areas of investigation in the IS research traditions

IS Research traditions	Potential areas of investigation
Behavioral Information Systems Research	Which factors drive the adoption of quantum computing by individuals, groups, and organizations?
	How should a training agenda be developed that helps IT leaders acquire the necessary knowledge to make informed decisions regarding quantum computing?
	How important is trust in quantum computing and how can it be increased?
	Which strategic process models facilitate the integration of quantum devices into organizational structures?
	How should organizations orchestrate the interaction of quantum computing and classical computing?
Design Science Research	How can quantum computing facilitate calculations for solving optimization problems?
	How can the simulation of the behavior of complex systems benefit from quantum computing research?
	What are the implications of quantum-related speed-ups for machine learning applications?
	How can quantum computing accelerate and improve the analysis of large datasets?
	How can new applications and workflows be designed that jointly leverage advances in classical computing, quantum computing and Artificial Intelligence?
	What are the implications of post-quantum and quantum cryptography for the security of Information Systems?
Economics of Information Systems Research	How can we assess the business value of quantum computing in different application fields?
	What is the (monetary) impact of quantum-related innovations on a company's business model?
	What are the requirements for a vital ecosystem of startups, technology companies, investors and research institutions and how does this environment foster innovation in quantum computing?
	What are the economic consequences of quantum computing for the society?
	How can organizations measure efficiency gains in business process design and product development?
	How can governments help quantum computing startups grow?
	Which business problems should be prioritized when allocating resources for quantum computing projects?

agenda complements previous work by Rietsche et al. (2022) and aims to identify potential areas of investigation in the IS research traditions, esp. in behavioral science, design science, and economics of IS (Abbasi et al. 2016; Rossi et al. 2019).

Behavioral Information Systems Research. The behavioral science paradigm sheds light on the human and organizational behavior (Bariff and Ginzberg 1982). As with every technology, quantum computing is not a universal solution to every problem that companies face. Quantum computing is likely to perform specific tasks with a considerable performance increase in comparison to traditional systems. For other tasks, traditional systems are preferable. Besides, the installation of quantum devices in business processes will likely demand further structural and technological changes in organizations. That said, the adoption of quantum computers might not be a fruitful endeavor for every business. IT leaders should therefore not only develop a deep understanding of quantum computing, but also domain knowledge and integration expertise. Quantum computing is hard to understand, even for experts. If quantum computing is to become a general-purpose technology widely applied in practice, it is crucial to democratize basic knowledge about its inner workings to promote the broad acceptance and adoption of the technology by individuals, groups and organizations. Based on the experience with the emergence of previously new computing paradigms, we can expect research that examines the drivers and obstacles for the adoption and diffusion of quantum computing such as early work in the area of grid and cloud computing (e.g., Benlian et al. 2018; Messerschmidt and Hinz 2013). It is also very important to develop a training agenda that sufficiently educates people about fundamentals while at the same time not overwhelming them with excruciating details. To design such an agenda, we must first better understand what the required fundamentals are and how to present them to people. Examining organizational requirements and developing strategic process models that facilitate the integration of quantum devices into organizational structures, therefore, constitutes an increasingly important research direction. Their interdisciplinarity and proximity to practice make Information Systems researchers particularly suited to tackle this problem in a way that provides practitioners with a helpful strategic framework.

Design Science Research. The design science paradigm aims to study the creation of artifacts, which help increase human and organizational capabilities (Hevner et al. 2004). Design research in quantum computing offers numerous questions that researchers can examine. First, almost every industry faces optimization problems under economic, technical, and other constraints. Examples range from the allocation of (human) resources, capacity, as well as shift planning and logistical routing to the planning of energy consumption. Quantum computing might facilitate calculations for solving optimization problems and provide large-scale operations that are currently out of reach (Egger et al. 2020). Simulation is another area of concern. Modeling and simulating the behavior of complex systems is a vital task in all areas that rely on the emulation of the physical world to understand the structure and properties of the material on a molecular level. Recent work suggests that in the domain of simulations, today's NISQ devices may already enable improvements over traditional computing systems (see, e.g., Poulin et al. 2014). Fields that would benefit from quantum-based simulations include fertilizer (Reiher et al. 2017), sequence analysis or genetics (Emani et al. 2021), and material science (Bauer et al. 2020), possibly enabling the design of new materials that could better resist corrosion or prove better energy storage units than current battery technologies. Quantum machine learning (QML) is at the intersection of quantum computing and machine learning and increasingly attracts the attention of researchers and practitioners alike (Schuld and Killoran 2019). The capability of quantum computing to speed-up optimization problems has considerable implications for (supervised) machine learning methods, especially those that project data points into higher dimensional spaces to identify separating hyperplanes for classification (e.g., support vector machines and neural networks). Besides these positive implications, quantum computing also has the potential to provide significant threats, e.g., to the field of cryptography. Hence, academia and industry are undertaking efforts to prepare against quantum attacks. Two solutions are currently being discussed and implemented. On the one hand, *post-quantum* or *quantum-resistant cryptography* depicts a research area where cryptographers study and design new applications to encrypt messages using conventional hardware and traditional mathematical operations that pose an intractable challenge even for quantum computers. Besides, academic research also pays more and more attention to *quantum cryptography*: By harnessing properties of quantum superposition and entanglement, quantum systems themselves might ironically provide the remedy against the threat they pose for encryption systems. Quantum cryptography, sometimes also referred to as quantum key distribution (QKD), effectively harnesses the pure random nature and the no-cloning property of quantum states as a basis to generate completely random encryption keys (Gisin et al. 2002). While computer scientists dominate the research in quantum simulation, optimization, machine learning and cryptography so far, the Information Systems community can also contribute to these design-oriented research fields and especially consider socio-technical aspects when developing engineering methods for all life-cycle phases of Information Systems. Further topics include, but are not limited to, quantum requirements engineering, conceptual modeling, algorithm design, management and analysis of large datasets with quantum technologies, software engineering methods for quantum-based Information Systems, quality assessment, and considerations of the organizational context of these new types of Information Systems.

Economics of Information Systems. Quantum computing will provide economic consequences for companies and society like many other disruptive technologies before (Aral et al. 2013). Hence, examining the economic impact of quantum-related innovations on a company's business model becomes an important research area. Topics may also include the identification and measurement of efficiency gains in terms of business process design or product development. The history of traditional computing suggests that increases in the performance of processors and associated technological advances relatively reliably follow an exponential trend and will then affect the economy and society (see for example research by Hitt and Brynjolfsson 1996). As of today, it remains open to what extent quantum computing will undergo similar developments. Given the fact that the real business value of quantum computing is difficult to assess, research in this area becomes even more important. Gaining a better understanding of the way quantum technologies progress is important for better anticipating and planning organizational changes in response to the rise of quantum computing. Apart from incumbent firms pushing the frontiers of quantum computing, startups play an increasingly important role, too. The number of such startups has risen dramatically in the last decade, many being university spin-offs. Between 2012 and 2019 private investors alone funded 52 quantum-technology startups (Gibney 2019). This includes both companies focused on the development of quantum hardware (e.g., IonQ and QuTech) as well as those focused on quantum software and algorithms (e.g., Zapata Computing and JoS Quantum). The emerging quantum ecosystem of startups, technology companies, investors and research institutions provides numerous opportunities to study the development and evaluation of quantum-related business models in the near-term future.

In sum, accelerating discoveries in the field of quantum computing make it increasingly important for Information Systems researchers to become quantum-ready and make the first steps towards establishing an agenda for Information Systems research around quantum computing. With the article at hand, we hope to inspire research work and related papers on the wide-open field of IS research that deals with the new, potentially disruptive technology of quantum computing.

Funding Open Access funding enabled and organized by Projekt DEAL.

References

Abbasi A, Sarker S, Chiang RH (2016) Big data research in information systems: toward an inclusive research agenda. J Assoc Inf Syst 17(2):3

Almudever CG, Lao L, Wille R, Guerreschi GG (2020) Realizing quantum algorithms on real quantum computing devices. In: 2020 Design, Automation & Test in Europe Conference & Exhibition. IEEE, New York, pp 864–872

Aral S, Dellarocas C, Godes D (2013) Introduction to the special issue – social media and business transformation: a framework for research. Inf Syst Res 24(1):3–13

Arute F, Arya K, Babbush R et al (2019) Quantum supremacy using a programmable superconducting processor. Nat 574(7779):505–510

Ballance CJ, Harty TP, Linke NM, Sepiol MA, Lucas DM (2016) High-fidelity quantum logic gates using trapped-ion hyperfine qubits. Phys Rev Lett 117(6):060504

Bariff ML, Ginzberg MJ (1982) MIS and the behavioral sciences: research patterns and prescriptions. ACM SIGMIS Database: DATABASE Adv Inf Syst 14(1):19–26

Bauer B, Bravyi S, Motta M, Chan GK-L (2020) Quantum algorithms for quantum chemistry and quantum materials science. Chem Rev 120(22):12685–12717

Benlian A, Hess T, Buxmann P (2009) Drivers of SaaS-adoption – an empirical study of different application types. Bus Inf Syst Eng 1(5):357–369

Benlian A, Kettinger WJ, Sunyaev A, Winkler TJ, Guest Editors (2018) The transformative value of cloud computing: a decoupling, platformization, and recombination theoretical framework. J Manag Inf Syst 35(3):719-739

DiCarlo L, Chow JM, Gambetta JM et al (2009) Demonstration of two-qubit algorithms with a superconducting quantum processor. Nature 460(7252):240–244

Egger DJ, Gambella C, Marecek J et al (2020) Quantum computing for finance: state of the art and future prospects. IEEE Trans Quantum Eng. https://doi.org/10.1109/TQE.2020.3030314

Emani PS, Warrell J, Anticevic A et al (2021) Quantum computing at the frontiers of biological sciences. Nat Methods 18:701–709. https://doi.org/10.1038/s41592-020-01004-3

Feynman RP (1982) Simulating physics with computers. Int J Theor Phys 21(6/7)

Flamini F, Spagnolo N, Sciarrino F (2018) Photonic quantum information processing: a review. Rep Progr Phys 82(1):016001

Gibney E (2019) The quantum gold rush. Nat 574(7776):22–24

Gisin N, Ribordy G, Tittel W, Zbinden H (2002) Quantum cryptography. Rev Mod Phys 74(1):145

Hamel DR, Shalm LK, Hübel H et al (2014) Direct generation of three-photon polarization entanglement. Nat Photonics 8(10):801–807

Hevner AR, March ST, Park J, Ram S (2004) Design science in information systems research. MIS Q 28(1):75–105

Hitt LM, Brynjolfsson E (1996) Productivity, business profitability, and consumer surplus: three different measures of information technology value. MIS Q 20(2):121–142

Humble TS, Thapliyal H, Munoz-Coreas E, Mohiyaddin FA, Bennink RS (2019) Quantum computing circuits and devices. IEEE Des Test 36(3):69–94

Kerenidis I, Prakash A (2016) Quantum recommendation systems. arXiv preprint. arXiv:1603.08675

Lidar DA, Chuang IL, Whaley KB (1998) Decoherence-free subspaces for quantum computation. Phys Rev Lett 81(12):2594

Messerschmidt CM, Hinz O (2013) Explaining the adoption of grid computing: an integrated institutional theory and organizational capability approach. J Strateg Inf Syst 22(2):137–156

Monz T, Nigg D, Martinez EA et al (2016) Realization of a scalable Shor algorithm. Sci 351(6277):1068–1070

Preskill J (2018) Quantum computing in the NISQ era and beyond. Quantum 2:79

Popkin G (2017) China's quantum satellite achieves 'spooky action' at record distance. Sci Mag, 15

Poulin D, Hastings MB, Wecker D, Wiebe N, Doherty AC, Troyer M (2014) The Trotter step size required for accurate quantum simulation of quantum chemistry. Quantum Inf Comput 15(5–6):361i–3384

Pompili M, Hermans SL, Baier S et al (2021) Realization of a multi-node quantum network of remote solid-state qubits. arXiv preprint. arXiv:2102.04471

Reiher M, Wiebe N, Svore KM, Wecker D, Troyer M (2017) Elucidating reaction mechanisms on quantum computers. Proc Nat Acad Sci 114(29):7555–7560

Rietsche R, Dremel C, Bosch S, Steinacker L, Meckel M, Leimeister JM (2022) Quantum computing. Electron Mark 32:2525–2536

Rivest RL, Shamir A, Adleman L (1978) A method for obtaining digital signatures and public-key cryptosystems. Commun ACM 21(2):120–126

Rossi M, Mueller-Bloch C, Thatcher JB, Beck R (2019) Blockchain research in information systems: current trends and an inclusive future research agenda. J Assoc Inf Syst 20(9):14

Schuld M, Killoran N (2019) Quantum machine learning in feature Hilbert spaces. Phys Rev Lett 122(4)

Shor PW (1994) Algorithms for quantum computation: discrete logarithms and factoring. In: Proceedings 35th annual symposium on foundations of computer science, pp 124–134

Shor PW (1996) Fault-tolerant quantum computation. In: Proceedings of 37th conference on foundations of computer science. IEEE, New York, pp 56–65

Shor PW (1998) Quantum computing. Documenta Math 1(1000):467–486

Trabesinger A (2017) Quantum computing: towards reality. Nat 543(7646):S1–S1