How could quantum computing shape information systems research - An editorial perspective and future research directions

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Abstract: Quantum computing promises to be the next frontier of change that will transform the information and communication technology ecosystem. Governments and multinational firms have announced large grants and research projects involving quantum computing. These projects are envisioned to solve extremely complex computational problems that may bring transformational value to mankind at large. Information systems, as a discipline, is and will continue to be affected by this disruptive technology. In this article, we examine the advances in quantum computing and explore possible areas of theory development in information systems. Further, we discuss challenges and opportunities in quantum computing based on current technological developments in the field. We conclude by providing research directions regarding the adoption, usage, impacts, governance, and skills surrounding quantum computing at the individual, organizational, and national levels.

Keywords: Quantum computing; Theory building; Information systems; Emerging technology management; Information systems adoption; Information system impacts; Generative Artificial Intelligence.

1. Introduction

Quantum computing is a technological innovation that uses principles of quantum mechanics to solve extremely complex computational problems (Benioff, 1980). These complex problems are typically too difficult for the traditional computers that uses a binary coding system. In the traditional computing systems, some of these complex tasks had a computational complexity that is non-deterministic polynomial-time hardness, and so earlier there was a quest to find newer types of artificial intelligence algorithms which could address these computation needs (Kar, 2016). Some examples of these computationally complex problems are identifying formulations of medicines, cracking the genetic codes of species, projectile motion in aerospace engineering and similar areas in science. Traditional supercomputers which are used need very high processing speed and capabilities, typically in Petaflops and Exaflops, in high performance computing systems. However, these high performance computing systems have excessive energy consumption and have adverse ecological impacts (Dwivedi et al., 2022). This is where quantum computing is envisioned to be able to change the computing ecosystem and address the needs surrounding more efficient systems infrastructure.

Quantum computing is a type of computing that takes advantage of the principles of quantum mechanics, a branch of physics that deals with the behavior of very small particles at the quantum level (Deutsch, 1985). Unlike classical computers, which use bits to represent information through a combination of 0s and 1s, quantum computers use quantum bits, or qubits. In doing so, a variety of very complex computational tasks can be completed with greater efficiency using quantum computing which otherwise traditional computing would be unable to undertake. There has been deliberations on how quantum computing can both provide benefits to the society at large through improved computing capabilities and responsible innovation from a utopian viewpoint (Inglesant et al., 2021). There has also been deliberations how it may lead to a race for quantum advantage in a dystopian perspective as it proliferates across geographical boundaries (Rosch-Grace and Straub, 2022).

A simple breakdown of some key concepts on which quantum computing is built includes:

a) Qubit: This is the basic unit of quantum information and draws parallel to the bits in traditional computers. Qubits can exist in multiple states simultaneously unlike the binary states of bits due to a property called superposition. This allows quantum computers to perform many calculations simultaneously.
b) Superposition: This allows quantum computers to consider multiple possibilities at the same time. Classical computers, in contrast, would have to go through each possibility individually and one at a time(Benioff, 1980).
c) Entanglement: Qubits can be entangled, which means the state of one qubit is directly related to the state of another, regardless of the distance between them. This enables quantum computers to process information in a highly interconnected way (Williams & Clearwater, 1998).
d) Tunneling: Quantum tunneling is a mechanism in which particles (e.g., electrons) pass across a barrier (Kop et al., 2023), a phenomenon that was not possible in classical computing due to insufficient energy to surmount.

Quantum computing promises to be one of the major drivers of technological change in the next decade. Industrial innovations, processes, products and services are largely projected to be impacted by this new form of computational breakthrough that is envisioned to drastically transform the way software and hardware ecosystems currently operate in organizations. So, why is quantum computing potentially a game changer? Some of the reasons are attributed to the following ability of quantum computing:

a) Speed: Quantum computers have the potential to solve certain types of problems much faster than classical computers. They can handle complex calculations, like factoring large numbers or simulating quantum systems, that would take classical computers an impractical amount of time (Shor, 1999) .

b) Parallelism: Quantum computers can process many possibilities simultaneously, making them well-suited for tasks such as optimization problems, machine learning, and cryptography (Rieffel and Polak, 2000).
c) Exponential Advantage: As the number of qubits increases, the processing power of a quantum computer grows exponentially. This gives quantum computers the potential to outperform classical computers in specific applications (Shor, 1999).
d) Breaking Current Encryption: Quantum computers could potentially break widely used encryption algorithms, threatening the security of data that relies on these algorithms. This has led to an interest in developing quantum-resistant cryptographic techniques (Fisher et al., 2014; Mavroeidis et al., 2018).

McKinsey predicts that the quantum computing markets will cross 1 trillion United States Dollars (USD) by mid-2030s, and this growth will be driven by consumption in financial services, chemical manufacturing, automotive, technology, media, and telecommunications industries (Hazan et al., 2020). These statistics indicate how much impact quantum computing is envisioned to have on the future industrial processes that will look to transform themselves digitally in the coming decade. However, the reports also indicate that there are technological factors that will guide the success of capabilities envisioned through quantum computing and organizational factors that may empower successful adoption and diffusion (Gao et al., 2023). Therefore, this requires a deeper introspection among information systems scholars to examine the challenges and solutions that quantum computing may bring to the digital transformation journey of organizations and how the technology could disrupt current computing ecosystems.

Among corporations, technology advocacy and consulting firms like McKinsey are not the only organizations heavily optimistic about the future of quantum computing. Technology user firms are also upbeat about the possible future use cases of quantum computing to solve complex problems. For example, BASF (2021) has invested over 30 million USD in quantum computing as its leadership feels that classic digital approaches are nearing the limits of their capabilities and quantum computing may empower firms to generate the needed computational ecosystem that can handle very large volumes of data and use artificial intelligence to solve complex problems more accurately while reducing the time taken to arrive at the solution in the chemical manufacturing industry. Similarly, for investing in the core developments in quantum computing, IBM (2023) recently initiated a ten-year research collaboration with Cleveland Clinic to develop bio-medical and healthcare projects using quantum computing with the hope that it will enable identifying new medicines and treatments more quickly for care delivery. It is envisioned that quantum computing technologies will help to address historic bottlenecks in scientific discoveries and potentially find newer and improved medications for patients with terminal and chronic diseases. Similarly, in March 2023, NVidia launched initiatives with the Israel Innovation Authority to support a collaboration to create a platform integrating quantum and classic computing capabilities (Wrobel, 2023). Similarly, a decades-long partnership with Fujitsu and Osaka University has recently created a fault-tolerant architecture using quantum computing platforms. This initiative seeks to solve computational business problems that are non-deterministic polynomial time, such as optimizing financial portfolios across asset classes, designing vehicle routing logistics networks that combine different types of vehicles and their suitability towards different routes, managing self-driven vehicles, and optimizing resource distribution (such as power usage/supply) in complex distributed systems (Fujitsu, 2023). These systems are perceived to create efficient platforms to improve implementation of smart cities, information assurance, cyber security, chemical and material development, among others.

In 2018 and through the national quantum initiative, the United States National Science and Technology Council launched the quest for quantum information science to guide research and developments in this space (NSTC, 2018). The NSTC report highlighted that policy interventions are needed to bolster scientific development in quantum information science, a smart workforce for current and future quantum needs, collaborations with industry, critical infrastructure, national security, and economic development, along with international research collaborations. With these objectives in mind, the US government initiated a 1.2 billion USD funding mechanism over a period of 5 years to support and spin quantum information science research. On similar lines in March 2023, the United Kingdom government published its national quantum strategy, a 10-year vision to be a leading quantum-enabled economy while recognizing the importance of quantum technologies for the United Kingdom's focus towards national development (UK Government, 2023). In fact, the government of United Kingdom reported that it would invest 2.5 billion GBP (3.2 billion USD) over a period of 10 years for the development of quantum computing, as it provides opportunities to fuel the next "Silicon Valley". The Government of France announced research grants of 1.8 billion Euros (1.95 Billion USD) for the development of capabilities in quantum computing (Dargan, 2023). Similarly, in April 2023, the Government of India approved a focused funding of 6000 crore INR (0.73 billion USD) among Indian research institutions to scale up the quantum research capabilities (Cabinet of Government of India, 2023; Dwivedi and Kar, 2023). IBM and the University of the Witwatersrand in South Africa has also started a research collaboration to expand its quantum computing activities to Africa through hackathons and research programs (Etim, 2022). Subsequently, IBM Research Africa extended this collaboration to 16 universities across Ghana, Ethiopia, Kenya, Nigeria, Senegal, Rwanda, South Africa, Tanzania and Uganda (Bright, 2019).

Some of the initiatives related to quantum computing have also been recently introduced in the Middle East. For example, the Technology Innovation Institute (TII) in Abu Dhabi established the Quantum Research Center (QRC) working on areas such as quantum cryptography, quantum sensing, and quantum communications (QRC, 2024) and currently has three qubits running on its Masdar City premises in Abu Dhabi (Wired, 2022). Similarly, King Abdullah University of Science and Technology in Saudi Arabia has financed developments in quantum computing by forming a partnership with Zapata Computing, a spinout from Harvard (KAUST, 2021). With a focus on the application of quantum technology to computational fluid dynamics, KAUST aims to distinguish itself from popular use cases of quantum computing (e.g., digital security) and focus on untapped areas such as CFD that will help advance other areas of sciences.

The Middle East has also seen an interest in quantum computing in the defense industry as well. For example, Qatar is making efforts to advance quantum technology in its national initiative on quantum computing. With an investment of $10 million from the government of Qatar, Hamad bin Khalifa University signed an MoU with a Qatari defense company along with the establishment of

Qatar Center for Quantum Computing (QC2) focusing on quantum computing, quantum sensing, and quantum communication (HBKU, 2022). Similarly, Türkiye has several university programs in quantum computing funded by the Air Force Office of Scientific Research (Dargan, 2022). Other programs in Türkiye include the Applied Quantum Research Center at İzmir Institute of Technology (Dargan, 2022), and QTurkey, a collaboration network in the area of quantum technology activities (QTurkey, 2024).

As per the global investments noted above, the following four focused areas are envisioned as part of this research initiative for research: 1) quantum computing, 2) quantum communication, 3) quantum sensing & metrology and 4) quantum materials & devices. Globally, across nations, as of June 2023, already grants of 10 billion USD have been planned for research in quantum computing by governments of different countries (Chakraborty, 2023). These trends among global governments and industry sectors indicate that quantum computing will be a disruptive technology. It is expected to affect the way organizations and individuals interact with and use these technologies in the future. As a disruptive technology, the adoption and use of quantum computing will result in radical transformation at the individual, organizational, and societal levels. In this editorial and to better understand the anticipated transformation associated with quantum computing, we ask the following questions and provide narratives to show the significance of our inquiries:

> Q1) How should information systems research evolve in the era of quantum computing technologies?
>
> Q2) What is the current state of developments in quantum computing?
>
> Q3) What are the opportunities and challenges in quantum computing for information systems research?
>
> Q4) What are the future research agendas in information systems discipline involving quantum computing?

In this editorial, we attempt to address the above questions. The remaining sections of this manuscript is structured in order of the questions listed above.

2. Current state and advances in quantum computing

The first conceptualization of quantum computing was made by Benioff (1980), whereby a microscopic quantum model of computer, based on quantum mechanics, as an extension of Turing machines was constructed. This was inspired by the mathematical foundations of quantum theory which was proposed in Neumann (1955). In 1982, Richard Feynman discussed a machine that would operate on quantum mechanical principles to simulate the behavior of one quantum system using another quantum system — essentially, a quantum simulator (Feynman, 1982). In 1985, David Deutsch of the University of Oxford proposed a quantum Turing machine, based on Alan Turing's pioneering work on the theoretical foundations of computation and what constitutes a general computer, and specified an algorithm designed to run on a quantum computer (Deutsch, 1985). Quantum computing exploits quantum mechanical phenomena to process information; it represents a paradigm shift from the classical computing paradigm since the classical computing system uses bits (Williams & Clearwater, 1998). At the intersection of research in quantum physics and theoretical computer science, the field took off in the mid-90s among academia when the concepts were yet to be recognized and focused upon as being relevant for industrial organizations and therefore yet to become national priorities. In 1994, the mathematician, Peter Shor, proposed an algorithm for a real world “killer application” of a quantum computer: the capability to factorize large numbers into their prime number factors exponentially faster than possible with a classical computer (Shor, 1994). This was when the computational capabilities of quantum computing first realized to be different and higher than the binary system of computing. However, until very recently, the variations of computational calculations which were doable using quantum information properties, such as superposition or entanglement, were relatively restricted.

In 2012, Serge Haroche and David Wineland were awarded the Nobel Prize in Physics “for ground-breaking experimental methods that enable measuring and manipulation of individual quantum systems” (The Noble Prize, 2012). Their work has profound implications for quantum information and quantum computing and was recognized by the Royal Swedish Academy of Sciences as being pathbreaking. While quantum computers sometimes enable solving non-deterministic polynomial hard (NP-hard) problems feasible in much less time for a wide variety of problems, they face accuracy issues and lack adequate error correction mechanisms. (Hazan et al., 2020). Similarly, Preskill (2023) highlights how developments like Shor’s algorithms enable quantum error corrections, which facilitate solving very complex problems at a faster rate. Kim et al. (2023) highlight how quantum computing enhances fault tolerance capabilities for processors when employing tensor network methods for processing very large matrix operations .

Fundamental discoveries continue to be a major thrust area in quantum computing (NASEM, 2018). As quantum computing moves steadily toward real-world applications, it is increasingly gaining prominence as a key area of research across applied disciplines like applied science and engineering (Elsevier, 2020). Developments in quantum computing are witnessed in both corporate and academic research (Coccia, 2024; Coccia et al., 2024; Bhasin and Tripathi, 2024). In academia, the focus is more on pushing the boundaries of knowledge and theories. In the corporate, the focus is on technology capability and application development. IonQ (2023) is expanding the commercial availability of its Forte quantum computer, bringing quantum computing closer to the point that customers can start running real-world applications. Nvidia (2023) reported in May 2023 that through its partnership with Rolls Royce and Classiq that they have developed the world’s largest quantum computing circuit for computational fluid dynamics for modeling the performance of jet engines. This development in quantum computing is envisioned to develop futuristic jet engines that support the energy transition with more sustainable aviation. These developments indicate how nations and industries are slowly and steadily gearing up to leverage the quantum computing wave through strategic collaborations and investments in research and innovation. JPMorgan Chase have started advocating possible usage of quantum computing in financial management like pricing, risk modeling, portfolio management, resource allocation, forecasting and recommendation engines (Herman et al., 2023).

Further, traditional quantum computing infrastructure has been planned, which may be dedicated and on-premise infrastructure, acquired or developed by the firm that uses it. This dedicated infrastructure for quantum computing application is costly to establish in most organizations which may not have suitable budget or manpower (Coccia, 2024). Emerging models for accessing quantum computing are being facilitated by cloud service providers where quantum computing is accessed and used as a service (Quantum Computing as a Service) in platforms like Microsoft Azure (Dargan, 2023). Quantum Computing as a Service (QCaaS) will enable greater access via the internet, and complex models may be integrated with cloud computing models, such as Data as a Service (DaaS) or Software as a Service (SaaS), to provide access to many firms that may lack the need, financial capital, or internal capabilities for dedicated, high-scale computing infrastructure.

An emerging area of research in quantum computing is Generative Quantum Computing. Zoufal et al. (2019) demonstrated how Quantum Generative Adversarial Networks can perform better using distribution learning and loading method with Qiskit on actual quantum processors (IBM Q Experience). These Generative Artificial Intelligence algorithms typically adapt two competing deep neural networks - a generator and a discriminator - which are trained alternately. Alternatively these architectures have an encoder and decoder working in conjunction (Dwivedi et al., 2023; Kar et al., 2023). Replacing either the generator, the discriminator, or both with quantum systems translates the framework to the quantum computing context (Zoufal et al., 2019). However more complex these deep neural networks, typically more effective the models are and more computational infrastructure they need. Quantum computing is perceived to make these generative models more efficient. However interestingly Hibat-Allah et al. (2024) demonstrates that quantum generative models like Quantum Circuit Born Machines, Transformers Architectures, Recurrent Neural Networks, Variational Autoencoders, and Wasserstein Generative Adversarial Networks are more efficient in the data-limited ecosystems than the other generative artificial intelligence models. These counter intuitive findings makes us wonder about the boundary conditions under which quantum computing efficiencies may be better.

3. Quantum computing in relation to information systems

Theory development in information systems started with a focus towards using reference theories, where we borrowed heavily from related disciplines. These theoretical deliberations often, however, started from a “non-IT ecosystem” and they were extended towards the “IT enabled ecosystem”. Recent deliberations surrounding theorizing in the “digital ecosystem” as an extension of the “IT ecosystem” shows that as context shifts, there is a need to re-examine new features, entities, interaction with stakeholders, and properties of these interactions beyond the traditional lens (Baiyere et al., 2023).

Since the capabilities and outcomes of the digital ecosystems are envisioned to be drastically transformed with the increased diffusion of quantum computing, it will present an opportunity to explore contexts that move beyond the “old wine in a new bottle”. In traditional theory building, much of the literature evolved by borrowing theoretical building blocks from related disciplines and contextualizing them to the digital phenomenon. However, the theoretical concepts like increased network economies, technology access, greater efficiencies in information flow dynamics, embeddedness of technological artifacts, new affordances, data analysis capabilities and nature of transformation requires studies to examine more intrinsic elements of the digital phenomenon that differs from the traditional theoretical building blocks (Baiyere et al., 2023). Other related concepts which may impact the adoption, usage and impacts of quantum computing could stem from literature involving digital ontology, digital embeddedness, digital transformation and artificial intelligence.

Quantum computing technologies are likely to expedite the growth of these capabilities in digital firms. We envision that with the adoption and usage of quantum computing embedded technological artifacts, there may be a need to theorize about new paradigms of knowledge arising out of the new affordances, usage and impacts of using quantum computing in different contexts by different actors. We may need to borrow heavily from related disciplines like engineering and physics to understand the "box of quantum computing" as an artefact having its own unusual characteristics which is different from the classical computer systems. Figure 1 illustrates this conceptual change that the IS discipline is likely to witness in the coming years.

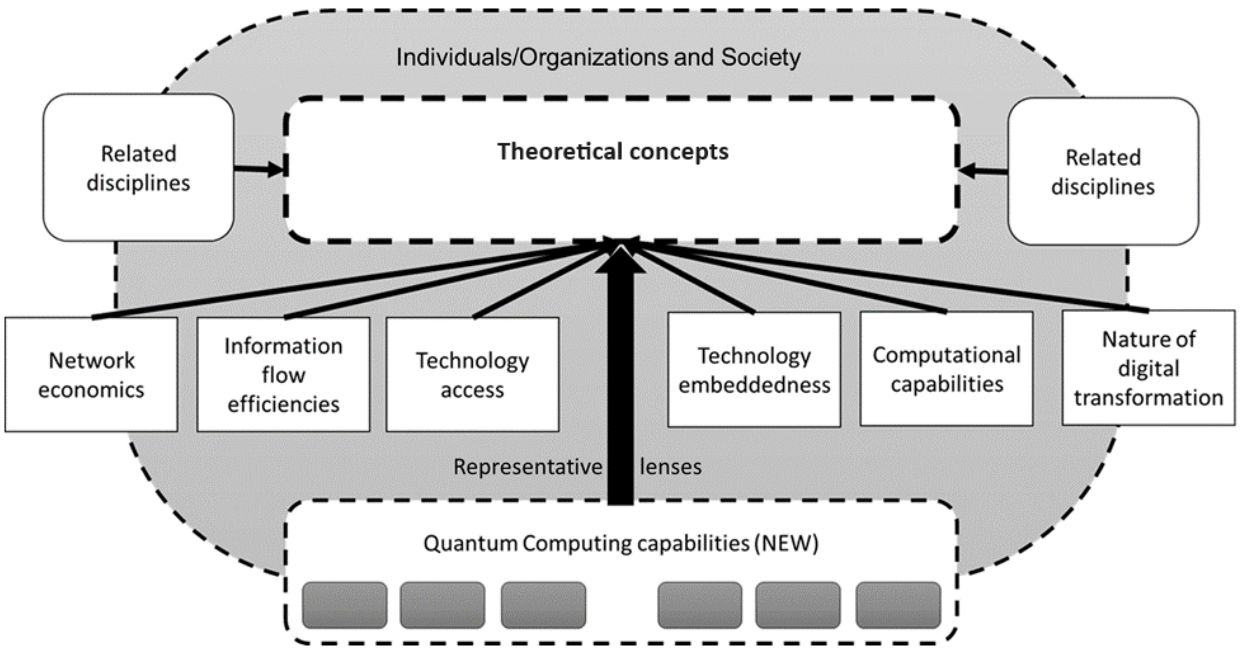

Fig 1: Positioning of quantum computing within Information Systems theories

Given that efficiencies and efficacies of computing infrastructure is going to be transformed with increased adoption of quantum computing, we foresee larger networks of organizations which can come together in a value-web to provide services and manufacture products. The scales of collaboration and operations across multiple organizations may witness increasing utility from network economics, which was rarely evident earlier because the scale was difficult to manage. oConversely, it may also experience a completely diminishing utility (Bova et al., 2023). Scaling up may have high costs for the participants in a network. These changes may also introduce different types of both intermediation and disintermediation among the networks. The nature of transaction costs, in these networks may also change and there may be a need to theorize differently about these digital networked ecosystems.

With increased adoption of quantum computing, information cryptography and information flow are likely to witness major transformation (Yang et al., 2023). Security issues, such as low-key rate vulnerability to denial of services and low key efficiencies, are likely to create challenges in quantum computing communications. Protocols of communication would need to evolve and theoretical knowledge surrounding facilitators and barriers of new communication systems using quantum computing may need revisiting. In addition, with quantum computing network utilization, the impacts of this use may need discovery of new factors which may be both utopian and dystopian, across different stakeholders.

Quantum computing adoption may be heavily dependent on factors driving access at both the firm level and at the individual level. Early days of quantum computing technologies may have prohibitively high cost, both variable and fixed. For example, a 2000 qubit quantum computing may cost $15 million (Dargan, 2023). Upfront investments in quantum computing infrastructure may not be possible for smaller and medium sized firms, owing to the capital costs involved. Talent needs in quantum computing would also be expected to increase significantly (Piattini, 2020). Similarly, talent trained in quantum computing may be difficult to attract in many firms, as they may be higher in demand, as compared to opportunities in the initial stages, and therefore wages and long-term opportunities may drive preferences in choosing an employer. However, cloud-based quantum computing models, may help to bridge this gap of access due to financial constraints and generate new models of technology access since capital investments for building a new quantum computing infrastructure would be significantly reduced. Firms and nations with less access to financial and technological resources may be able to use applications of quantum computing for business growth and societal developments. It may also be possible for startups to create platforms which leverage upon quantum computing as a service for developing their business models.

Further, the introduction of quantum computing in firms would be expected to transform organization functions, processes and subsequently organization structures. If firms adopt quantum computing, there would be changes in process efficiencies and productivity. Structures within organization may also evolve as these technological interventions may introduce higher degree of process automation and reduce human intermediation. There would be an inherent need to explore the processes of successful drivers (and barriers) facilitating this transformation as well as the outcomes, in contrast to many existing perspectives (for example, Robey and Boudreau, 1999). This process of adopting and using quantum computing may be envisioned as an extension of the technology mediated organization transformation wherein the relational and structural embeddedness of the quantum computing artifact may impact structural conditioning, social interaction within the organization and outside the organization, and structural elaboration which may be driven by ostensive or material aspects of the extended interaction among the firm, user and technology (Volkoff et al., 2007). We envision quantum computing to be embedded in organizations beyond traditional information systems (Polites and Karahanna, 2013). Since users within organizations may witness higher levels of both availability and accessibility of quantum computing applications outside the premises of the organization and into their personal time as well, there may be greater levels of ubiquity, convenience, interactivity, personalization and localization witnessed in the use of these applications. Employees with different skills may be needed, which firms may face difficulty in recruiting, given how niche these skills are (Ten Holter et al., 2023). We may, however, need to move beyond the existing theories for examining these changes to organizations, processes and users given the nature of embeddedness of quantum computing we envision. Further, it may be important to study network embeddedness also among users working in partnering firms in a value web due to the intricate complexities of platform economics (Lin et al., 2009; Liu et al., 2019).

A breakthrough is envisioned in computational capabilities with quantum computing. This breakthrough may happen for mining information for big data analytics for cognitive intelligence (Gupta et al., 2018). The computational capabilities of firms may allow them to use information assets to bring about a major change in the way they create value and also innovate in new business models. quantum computing may also enable large scale centralization of data in platform economies which may lead to market efficiencies or disruptions at scale, due to variety and volumes in the data at the computing infrastructure level; unforeseen innovations in business processes and outcomes at the firm level; attention, judgment and motivation of users at the individual level (Phelan & Wenzel, 2023). These changes may however enable firms to collect at scale trace data and analyze this trace data for product and service improvements and provide “magic solutions”. Researchers may also be able to use this trace data to study the interaction, usage, user experience and impacts of these technological innovations and platforms using computationally intensive theory building methods (Kar and Dwivedi, 2020; Kar et al., 2023). Use of artificial intelligence and machine learning algorithms on trace data may enable researchers to examine the usage of these applications and theorize based on honest signals captured from users and subsequently retained as footprints in these platforms.

Last but not the least, the nature of digital transformation envisioned in firms, may undergo a change (Kraus et al., 2022). This may introduce newer affordances from scale besides network effects. Differences may be observed in structural changes, ways of value creation, use of these digital artifacts, nature of user behavior and dynamic capabilities of the organizations in the platform. The nature of digital transformation may also impact the way the stakeholders engage and co-create value over large scale platforms which may be possible to manage due to quantum computing based applications at a scale which would otherwise be infeasible. Further models of business process outsourcing may also evolve among the firms undergoing digital transformation based on different capabilities of the firms like consultative capabilities, orchestration capabilities, standardization capabilities, stakeholder network management capabilities, knowledge access capabilities and generation of actionable insights capabilities (Mazumder and Garg, 2021). Because of quantum computing adoption in enterprise applications, we envision that orchestration capabilities, stakeholder management capabilities and generation of actionable insights to be enhanced significantly, given the way quantum computing could affect these organizations.

Other related concepts which may impact the adoption, usage and impacts of quantum computing could stem from literature involving digital ontology, digital embeddedness, digital transformation and artificial intelligence. There may be more lenses that researchers may foresee while working in this area, which involves the design, adoption, usage, and impacts of quantum computing for different stakeholders of the ecosystem.

4. Challenges

While quantum computing brings tremendous benefits, quantum computing also poses many challenges to society. One of the top challenges is related to cybersecurity since quantum computers could be used by cyber criminals to break many existing encryption algorithms (Chen et al., 2016) and hack numerous information systems people use in their daily lives such as banking, credit cards, utilities and public transportation. The consequences include an increased number of security incidents such as data breaches, stealing of sensitive information, and thefts of digital valuables (Faruk et al., 2022) if organizations fail to adopt stronger encryption algorithms such as quantum cryptography algorithms to protect their systems. On the other hand, quantum computers will also become a target for security attacks when quantum computers are used to process sensitive or valuable information (Szefer, 2023). For example, Szefer (2023) indicates that anyone who pays for access to cloud-based quantum computing services could potentially run arbitrary quantum circuits to attack the underlying quantum computers.

Furthermore, at the country level, it is challenging to ensure that benefits of quantum computing are equitably distributed across countries. The lack of resources will be a significant challenge and a barrier to the adoption of quantum computing in developing countries. Unequal access to quantum computing could not only negatively influence the security of cyberspace but also the national security, and cause a shift in global social, economic, military, and geopolitical power dynamics, making countries without quantum computing capabilities more vulnerable.

Another challenge is related to quantum education and workforce development (White House OSTP, 2022). Organizations need to have a quantum-literate workforce to reap the benefits of quantum computing while addressing talent challenges caused by quantum computing. There will be a talent shortage for people with expertise in quantum computing and technology and the quantum talent shortage is viewed by some as a national security vulnerability (Howell, 2023). Developing and training a competitive workforce with quantum-related technology skills is time-consuming since it has a steep learning curve and requires the development of general science, technology, engineering, and math (STEM) skills, and quantum-specific expertise. In addition, it requires a solid understanding of what the quantum industry needs in terms of skills and knowledge for different job roles in the emerging quantum era (Hughes et al., 2022). Without such understanding, it is challenging to develop effective curricula and courses that adequately prepare a competitive workforce to meet the needs of the quantum industries. Furthermore, developing or those non-superpower countries will face a serious talent challenge in recruiting and retaining domestic talent to protect their information systems and cyberspace in the post-quantum era since those with the appropriate quantum technology skill sets are likely to be lured away by developed countries or the large financial institutions and technology companies that can offer generous compensation. Quantum workforce availability is expected to be a critical bottleneck in many industries and countries (Chow et al., 2022).

There is also a challenge to develop a sustainable quantum computing and technology ecosystem comprising technology providers, start-ups, venture capitals, consulting firms, businesses, governments, professional societies, and academic institutions since there is a lack of governance, regulation, and standards for many aspects of quantum computing and technology. Governance, regulations and standardization need to be developed to support responsible development and scale-up of quantum applications, enabling better communication, collaboration and interoperability while mitigating risks of incompatibility (Chow et al., 2022). Strategies are needed to bring various stakeholders, including industries and academia together to find feasible business models and develop a sustainable quantum computing and technology ecosystem for adding business value across a wide range of application areas and accelerating the adoption and commercialization of quantum computing and technologies (Bongs, Bennett, & Lohmann, 2023).

5. Opportunities

As quantum computing is likely to be disruptive to existing businesses, it is essential to plan and develop a sustainable quantum computing ecosystem early on and produce effective use cases and applications for businesses and different industry sectors. Building a sustainable quantum computing ecosystem will help expand the user base, create demands and business opportunities, and support more users in adopting and building practical applications using quantum technologies (Rietsche et al., 2022). To do so, it is vital to help more organizations understand quantum computing's impacts on their business or industries, assess their quantum readiness and formulate a quantum computing and technology strategy, which is important for reaping the benefits of quantum computing and building a sustainable quantum computing ecosystem. An example of such efforts is Duality[1] , which is the first accelerator program in the US exclusively focused on supporting innovative quantum startups. Resources and support have been provided to assist quantum startups with their technology and business plan development efforts.

Many people will choose to use cloud-based quantum computing services (e.g., Azure Quantum, Amazon Braket) to avoid the hassle of installation and maintenance. Cloud-based quantum computing services allow people to subscribe to the quantum computing services that they need and pay for whatever they consume (Ur Rasool et al., 2023). It is necessary for quantum computing, domain and financial experts to collaborate, refine different pricing and other financial models, and determine the strategies for quantum resource distribution, customization and pricing.

Quantum computing is expected to be integrated with artificial intelligence (AI) to revolutionize AI capabilities by dramatically speeding up computations, performing optimization tasks, solving complex problems, and enhancing problem solving and decision-making across a wide range of sectors. Information systems researchers could help identify specific applications and problems in a wide range of areas, such as financial services, insurance, healthcare, manufacturing, transportation, natural resource management, and supply chains that are computationally challenging for conventional computers and for which quantum computing algorithms are

[1] https://www.dualityaccelerator.com/

promising (Egger et al., 2020). For example, quantum computers can be used to reduce the time needed for machine learning training and improve the capabilities of AI in solving challenging real-world problems related to financial prediction, asset pricing, risk minimization, fraud detection, routing and scheduling, and portfolio optimization (Orús, Mugel, & Lizaso, 2019; Ur Rasool et al., 2023). IS researchers could play a role in creating a collaborative community to co-create effective and accessible use cases related to quantum artificial intelligence by serving as liaison among quantum computing, artificial intelligence, and the business communities.

Information systems researchers could contribute by analyzing and identifying complex problems involving multiple variables and constraints, conducting feasibility and requirement analysis for effective implementation of quantum computing applications and integration, and assessing the impact and return of investment for quantum computing implementation and operation. It is worth mentioning that requirements of quantum computing for one application area, such as healthcare, is unlikely to be generalizable across other application areas. For example, the requirements for drug discovery can be very different from the requirements for vaccination development (Ur Rasool et al., 2023). Therefore, implementing or integrating quantum computing applications in different areas requires consideration of multiple factors for effective implementation and operation (Ur Rasool et al., 2023), which are suitable for information systems researchers to leverage their expertise.

6. Implications for practice and policy

At the individual level, it is important to provide inclusive training and learning opportunities to students and employees. This raises awareness, heightens proficiency and can result in quantum computing user adoption and use. It is crucial to address talent shortage in the future quantum workforce by investing in early quantum education to develop K-12 students' interest in learning about quantum computing and technologies. Educational pathways and workforce development opportunities including internships, apprenticeship and externships need to be developed to provide hands-on learning opportunities to further develop technical expertise in quantum computing and technologies. Individuals with expertise in quantum computing shall be provided with business support and entrepreneurship opportunities to apply quantum technology to commercial applications and problem solving.

At the organization level, commitment of upper management is crucial for adoption of quantum computing. Chief information officers, chief technology officers, and other leaders in organizations need to begin their efforts in preparation, such as planning organizational digital infrastructure, formulating quantum computing strategies, and upskilling their technical employees to make their organizations quantum-ready as soon as commercial quantum computers become readily available (Biondi et al., 2021). These leaders shall assess the current level of awareness and knowledge regarding quantum in their organization since there is a shortage of skilled workforce in this area. Organizations need employees with the quantum expertise, application domain expertise and business expertise to collaborate as a team, explore potential use cases, and experiment with applications of quantum computing to determine its feasibility, competitive advantages and business values for their organizations. Evidence has indicated that national quantum research initiatives continued to be challengeddue to skill shortages (Ten Holter et al., 2023).

Industry and governments need collaborate by developing guidelines to support quantum computing innovation, adoption and scale across sectors. Ethical guidelines need to be developed to prepare and support users or customers who adopt and use quantum technologies in a safe and ethical way. With broader input from relevant stakeholders and communities, governments can develop policies and regulations to ensure that the benefits of quantum computing are gained while mitigating potential risks and threats of the technology and its associated applications.

7. Research agenda in information systems

Rietsche et al. (2022) propose several research questions. We extend these research directions given the way we envision quantum computing can be used by future IS researchers in broadly four directions: 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. See the research questions listed in the Table 1 below for details.

We list some additional research questions (see the following table) related to the future research of quantum computing that may be useful for interested information systems researchers. These future research directions or research agenda are by no means exhaustive but intend to highlight some potential ideas that seem promising.

Table 1: Research agenda for the future

Potential areas for research	**Description of research agenda**
Impact of quantum computing on industry and society	● How can we study the affordances enabled by quantum computing in industrial and societal systems? ● How can we examine the impact of quantum computing on big data analytics, artificial intelligence, cybersecurity, finance, health care, supply chain, and other sectors? ● How would firm productivity be impacted in quantum computing platforms that involve multiple organizations? ● How can we explore the issues related to the emerging commercialization and market landscape of quantum computing? ● How can we assess the value and cost of quantum computing solutions, applications and use cases for

	end users? ● How can we assess the economical and societal implications of quantum computing? ● How can we explore the commercial applications, venture capitals, technology investment, entrepreneurship, and startups for a quantum computing ecosystem?
Impact of quantum computing on education and workforce development	● How to effectively integrate quantum computing into existing IS curricula? ● What teaching strategies, methods, and tools are effective to expose quantum computing to IS students? ● How to prepare and support IS students for future job opportunities and careers in the emerging and rapidly growing quantum computing industry? ● What could be complementary skills of workforce to gear up for a career as a specialist in quantum computing? ● How should pedagogies evolve in IS to cater towards skilling in a very technical area like quantum computing?
Governance and regulation of quantum computing systems	● How can policy makers facilitate developing effective governance models, measures and metrics for responsible and ethical use of quantum computing in specific sectors and across sectors? ● How can policy makers facilitate responsible development and innovation in quantum computing? ● How can we provide inputs for policy makers surrounding the development and enforcement of policy, regulations, and ethical guidelines for quantum computing? ● What adverse impacts may emerge from the adoption of quantum computing in organizational and social systems? ● How can the race for quantum computing competencies ensure social good?
Adoption of quantum computing systems	● What approaches could be used to develop paths or roadmaps for widespread adoption of quantum computing in organizations? ● How to prioritize use cases for good? ● How to develop an efficient and adequate pricing model for cloud-based quantum computing services that will meet customer's needs and requirements? ● What are necessary activities to institutionalize quantum computing in organizations?

	• theoretical framework for the design and implementation of quantum information systems • How can we model critical success factors for implementing quantum information systems? • How can we bridge the quantum computing divide across industries and countries? • How would individual and group productivity be impacted by quantum computing platforms? • How can individuals adopt and use quantum computing applications?

8. Conclusion

When quantum computing potentially reaches mainstream industries in abundance, it will be interesting to witness theoretical contributions which are built on rigorous empirical evidence. Quantum computing may enable definitions of new affordances (Payton and Kvasny, 2016), usage and impacts in organizations and it may be useful to establish these in a bottom-up approach. Alternatively, combinations of factors that leads to successful adoption, usage and impacts of different levels for enterprise quantum computing would be interesting to study. If studies undertake cross sectional studies for theory building, adequate care must be taken to ensure credibility of reporting, have appropriate sampling strategies, have a configurational perspective and have mixed- or multi-method designs (Maier et al., 2023). Mixed research methods may uncover new dimensions of how quantum computing can enable business processes and transformation of the firms and the platform economies, which may be interesting to study for IS researchers.

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