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## Quantum Computing and IS - Harnessing the Opportunities of Emerging Technologies

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# Quantum Computing and IS - Harnessing the Opportunities of Emerging Technologies

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## Abstract:

Emerging technologies have high potential for impact and are worthy of attention by the Information Systems (IS) community. To date, IS has not been able to lead the research and teaching of emerging technologies in their early stages, arguably because: (1) IS researchers often lack knowledge of the foundational principles of such emerging technologies, and (2) during the emerging phase, there is insufficient data on adoption, use, and impact of these technologies. To overcome these challenges, the IS discipline must be willing to break its own disciplinary research boundaries to go beyond software applications and their related management issues and start studying emerging technologies before they are massively adopted by industry. In this paper, we use quantum computing as an exemplar emerging technology and outline a research and education agenda for IS to harness its opportunities. We propose that IS researchers may conduct rigorous research in emergent technologies through collaboration with researchers from other disciplines. We also see a role for IS researchers in the scholarship of emerging technologies that is of introducing emerging technology in IS curricula.

**Keywords:** Emerging Technologies, Quantum Computing, IS Education, Time Lag Dilemma.

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# 1 Introduction

*“... nature isn't classical, dammit, and if you want to make a simulation of nature, you'd better make it quantum mechanical ...” – Richard Feynman*

Emerging technologies have potential for high impact on existing societal, economic, and industrial paradigms. Yet they are by definition characterized by high levels of uncertainty during the emergent phase, suggesting that their potential might ultimately not be realized (Rotolo et al., 2015). Despite this, they are worthy of attention by the Information Systems (IS) research community for several reasons. First, IS research can play a central role in understanding the potential impact of emerging technologies on organizations, society, and human behavior (Hovorka & Peter, 2019). As noted in Niederman et al. (2016), the development of a given technology may co-evolve with various social forces including skills development, consumer demand, and regulatory frameworks. IS researchers are well placed to examine these mutually reinforcing factors that may impact the trajectory of emerging technologies. Second, IS researchers may not accurately gauge the progress of an emerging technology if they are not collaborating “with people that are actively creating those (technologies)” (McGregor & Wetmore, 2009, p. 17). These people include researchers from other academic disciplines (e.g., natural sciences and engineering) and industry. Third, through these collaborations, IS researchers can engage, from the outset, in technology-related design decisions such as considerations for usability, user satisfaction, privacy, and security. Fourth, as educators, IS researchers can better prepare students as future leaders with transformational mindsets on what is, or could be, possible for emerging technologies (Jackman et al., 2016).

IS research has been slow in responding to emerging technologies. Consider blockchain as an example. Since its inception in 2008 (Nakamoto, 2008) it has spurred research interest in new application areas such as computer science (Rangasamy et al., 2011), finance (Moore & Christin, 2013), and political science (Atzori, 2015). However, it took 10 years for the first blockchain-based study (Beck et al., 2018) to appear in an AIS basket journal although a handful of blockchain studies were published in IS conferences and non-AIS basket journals. We queried the Web of Science using the term “quantum computing”, a phenomenon which began almost 40 years ago, and found that the search yielded zero papers in the basket journals. The delayed response to emerging technologies is partly because, as an applied discipline, IS usually researches technologies that are in widespread adoption using data from surveys, experiments, interviews, and digital traces to examine the interactions between the social system (e.g., an organization) and the technology system (see Johnson et al., 2019; Lee, 2004). Such data does not typically exist in the emergent phase of a technology.

However, emerging technologies can be better understood by examining their sociotechnical character (Sarker et al., 2019). The sociotechnical perspective, which has been described as the essence of the IS discipline, “considers the technical artifacts as well as the individuals/ collectives that develop and use the artifacts in social (e.g., psychological, cultural, and economic) contexts” (ibid. p. 696). Any emerging technology may be analyzed as a production network i.e., wherein the “focus is on the building of “systems of alliances,” which tie together inventors, research and development organizations, corporations, and governments who work together to develop new technologies and maintain their competitiveness” (Orlikowski & Iacono, 2001, p. 126) and/or as an embedded system i.e., one that is constantly evolving but existing within a complex and dynamic social context (ibid.). In the latter case, the focus would be on the social factors affecting the introduction of a technology and on how different user groups interact with the technology. We use quantum computing to demonstrate how an emerging technology may co-evolve with various social factors, and how IS researchers, as part of the consequential social system, may impact this co-evolution (Niederman et al., 2016).

Quantum computing is a model of computation that employs the rules of quantum mechanics to encode and process information (Marinescu & Marinescu, 2005). It has been identified as one of the most potentially disruptive technologies (Hazan et al., 2020). Conversations concerning the impact of quantum computing are already happening in other fields (e.g., computing, physics, and business). IS should not exclude itself from these conversations. Some prominent issues relevant for IS research in quantum computing include its threats to confidentiality and integrity of sensitive data, the design of cloud platforms for running quantum computing experiments, and cultivating value for organizations from new quantum applications such as artificial intelligence and search optimization. Although rare, early IS involvement in

development of emerging technology has proved valuable, for example, IS researchers drove the development of group systems technology (see Gallupe et al., 1992; Nunamaker et al., 1991).

At this juncture, it is important to highlight aspects of the IS field's approach to emerging technologies. IS researchers have not actively monitored or been involved in understanding the applications of emerging technologies in the early stage; and gaps exist between the courses being taught in IS curricula and the emerging technology skills that are needed in industry (Garousi et al., 2019). In this paper, we demonstrate how IS researchers can overcome these challenges in quantum computing research through collaborating with researchers from other disciplines who are actively developing quantum computing, and through introducing quantum computing in IS curricula. Although our aim is to generate insights that are generalizable to other emerging technologies, we recognize from the outset that different emerging technologies have different characteristics and may thus evolve on different trajectories from that of quantum computing. Regarding Orlikowski and Iacono (2001)'s charge that IS researchers should not ignore the IT artifact in their studies, we note that the quantum computing phenomenon at this stage is "an artifact in formation" (p. 126). As such, we emphasize the social components underpinning the design, development, and use of associated quantum computing platforms, as well as their potential impacts. These social components may differ from those of other emerging technologies (e.g., blockchain, IoT, artificial intelligence, etc.). Nevertheless, we propose a way of thinking about emerging technologies that advocates that the IS discipline should be quicker to act on the unique opportunities and threats that arise from their emergence.

The paper is organized as follows. We first describe the characteristics of emerging technologies and show how quantum computing fulfils the definition of an emerging technology. Then, we describe the challenges and advantages of teaching and researching emerging technologies in IS. Next, we propose a scholarly agenda for quantum computing in IS. Sidorova et al. (2008) categorize research published in prominent IS journals as belonging to the five areas: IT and organizations, IS development, IT and individuals, IT and markets, and IT and groups. We include in the proposed agenda examples of quantum computing-related research questions, based on the uncovered intellectual core of IS research that derives from Sidorova et al. (2008) that IS researchers interested in this phenomenon may explore. Taken together, our paper aims to foster (i) more proactive responses to emerging technologies by the IS community, and (ii) greater interest in quantum computing and its applications among the IS community.

The IS discipline is distinguished from related disciplines like computer science and information science by its emphasis on the sociotechnical. In contrast to past technologies that evolved while neglecting the social dimension, our key argument is that current emerging technologies like quantum computing could evolve on a different trajectory if their sociotechnical character is recognized from the outset. We argue that all information technologies are sociotechnical to the extent that key tenets of their design are determined by humans, and these decisions may prove consequential with time.

As an emerging technology gains prominence, what should be the role of the IS discipline? Save for a few exceptions, accounts of the sociotechnical perspective so far assume its application to established technologies. One can envision a passive response i.e., waiting until maturity and widespread adoption for serious IS inquiry. A more active – or rather proactive – response is also possible, one where, from the outset, IS researchers take an active interest in the technology, attempt to understand it, be involved in its design, and help shape its trajectory. We subscribe to the latter strategy.

Valuing the sociotechnical perspective as the organizing paradigm of IS research means appreciating the full spectrum of technologies and their potential or existing ramifications for organizational life as well as larger societal phenomena. An emerging technology like quantum computing would benefit from the unique perspective of IS researchers i.e., one that is guided by the sociotechnical axis. Meaningful conversations between driving disciplines such as theoretical physics and computer science on one hand, and IS scholars on the other, would reveal useful insights regarding the social dimensions of the use of the technology. Although quantum computing seems far from its physical realization, as IS researchers that are actively following the quantum computing phenomenon, we already observe various related areas where IS could contribute. Doubtless, other emerging technologies may also benefit from IS inquiry, but we use quantum computing as an example especially for its potential serious ramifications particularly in the realm of information security.

## 2 Quantum Computing: An Exemplar Emerging Technology

In this section, we explore why quantum computing can be classified as an emerging technology. We adopt the following definition of an emerging technology:

[A] radically novel and relatively fast growing technology characterised by a certain degree of coherence persistence over time and with the potential to exert a considerable impact on the socio-economic domain(s) which is observed in terms of the composition of actors, institutions and patterns of interactions among those, along with the associated knowledge production processes. Its most prominent impact, however, lies in the future and so in the emergence phase is still somewhat uncertain and ambiguous (Rotolo et al., 2015, p. 1828).

This definition highlights five characteristics of emerging technologies: radical novelty, prominent impact, coherence, relatively fast growth, and uncertainty and ambiguity.

### 2.1 Quantum Computing Exhibits Radical Novelty

Radical novelty arises from technologies built on completely different foundational principles or from existing technologies being applied in a completely different domain. Quantum computing exhibits radical novelty because it builds on completely different principles than classical computation. It employs quantum mechanics with a new way of encoding information, i.e., using qubits (quantum bits) which are capable of simultaneously storing multiple states (through superposition) (Brooks, 2012). This contrasts with classical bits, which can individually store a single state at a given time. Further, through the process of entanglement, it is possible by the laws of quantum mechanics to intertwine two qubits with each other so that their states are correlated even when separated by geographic distance. Taken together, quantum computing implies the possibility for solving problems that are beyond the capabilities of classical computing. Table 1 summarizes the radical novelty exhibited by quantum computing, by showing the distinctions between classical computers and quantum computers.

**Table 1. Distinctions Between Classical and Quantum Computers**

Criterion	Classical computers	Quantum computers
Randomness	Pseudo-randomness: Initial conditions determine outcome of computation	True randomness: The outcome is not determined by initial conditions
State of a bit	A classical bit can only be in one state at a single point	A qubit can be in multiple states at a single moment
Measurement	Does not affect the state of the measured system	Affects the state of the measured system

### 2.2 Quantum Computing Exhibits Potential for Prominent Impact

Prominent impact means that the technology must afford new pathways to disrupt competitive landscapes of multiple industries by creating new industries or transforming existing ones (Rotolo et al., 2015, p. 1831). Preskill (2018) advances three reasons why quantum computers would surpass the capabilities of classical computers. First, quantum algorithms perform exponentially faster for known problems that are computationally hard for classical machines. The best-known example is Shor's quantum algorithm for integer factorization, which runs in polynomial time and is much faster than the best-known classical factorization algorithm (Lomonaco, 2000). Second, it is experimentally feasible to demonstrate problems that quantum computers can solve that are beyond the capabilities of classical computers – this milestone is known as quantum supremacy (Harrow & Montanaro, 2017). Third, there is no known classical algorithm for simulating a quantum computer, even after decades of concerted efforts by physicists to do so (Preskill, 2018).

According to McKinsey & Company, information technology giants like IBM and Google, and early adopters in finance, material sciences, energy, travel, and logistics may start generating significant value from quantum computing by 2025 (Ménard et al., 2020). Quantum computing presents a threat to the confidentiality of existing secure data transformation systems. According to Mosca (2019), a 20% chance exists that quantum computers would be able to break RSA encryption in the next decade. That means sensitive data such as personal identification numbers, financial data, and health records are well within the scope of the quantum threat. All of these highlight the prominent potential impact of quantum computing.



## 2.3 Quantum Computing has a Coherent Expert Community of Practice

The coherence characteristics of emerging technologies relate to a growing expert community of practice (i.e., scientists and practitioners) that “adopts and iterates the concepts or constructs underlying the particular emerging technology” (Rotolo et al., 2015). Dozens of platforms are currently available for experimenting with quantum computing. A review of actively maintained quantum computing open source projects found a total 24 such projects maintained by a variety of private companies and research institutions, e.g., IBM, Google, Oak Ridge National Laboratory, and ETH Zurich (Fingerhuth et al., 2018). These projects cover a wide spectrum of quantum computing paradigms, e.g., discrete variable gate model, continuous variable gate model, and adiabatic computation. IBM’s Q Experience is one of the most mature platforms. It includes qiskit – a Python package for writing quantum programs, a graphical circuit composer for manipulating circuits, and a machine learning platform (Cross, 2018). Google recently released TensorFlow Quantum, which enables users to run quantum versions of machine learning algorithms (e.g., convolutional neural networks) on simulators (Broughton et al., 2020). Fortunately, quantum computing services can be accessed with high-level programming languages like Python, Julia, JavaScript, and C/C++ (Aleksandrowicz et al., 2019; Fingerhuth et al., 2018).

## 2.4 Quantum computing has Registered Relatively Fast Growth

Fast growth means that the technology registers increases across multiple dimensions, e.g., the number of scientists involved in furthering the technology’s products and services, the startups and patents related to the technology, the amount of funding, and the rate of adoption. Certainly, research and industry activity in quantum computing has accelerated in recent years. Public and private funding of quantum computing research has increased significantly. Since 2012, venture capitalists have funded more than 50 quantum computing hardware companies across the world, with total private funding in 2017 and 2018 amounting to \$450 million (Gibney, 2019). Quantum software has also attracted significant funding – \$110 million over the 2012 - 2018 period. The European Union has devoted more than €1 billion towards research in quantum computing, and many governments, e.g., the US, Canada, and Singapore, have injected hundreds of millions of dollars into quantum computing projects.

There has also been fast growth in the processing capacity of quantum computers. Quantum volume is a metric capturing “the useful amount of quantum computing done by a device in space and time” (Bishop et al., 2017, p. 1). IBM has doubled quantum volume since 2017, and randomized benchmarking error rates continue to decrease (Gambetta & Sheldon, 2019). IBM claims that increases in quantum computing capacity as captured by quantum volume over the past few years reflect Moore’s law for classical computing capacity. User activity in quantum computing has also registered fast growth, with the number of executions on the IBM Q Experience platform rising from 0.5 million in 2017 to 3 million in 2018 (Gambetta & Cross, 2018).

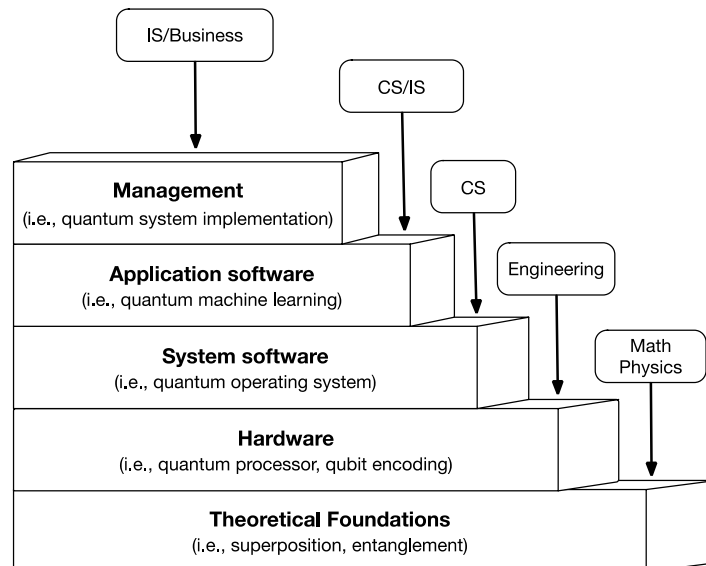
## 2.5 Quantum Computing’s Future Impact Exhibits High Uncertainty or Ambiguity

An emerging technology exhibits much uncertainty/ambiguity as to its future impact, meaning that it is difficult to predict exactly when the impact will be realized. Despite the progress that has been made, challenges remain to realizing the commercialization of quantum computing. Currently, the most advanced quantum computers have qubits numbering in the 50s to 70s (Arute et al., 2019; Preskill, 2018), a testament to the difficulties of scaling up the technology. More advanced programs for factoring huge numbers (numbers with 500 digits for example) will require thousands of qubits. Additionally, these computers still exhibit significant error rates (Preskill, 2018). This reflects the biggest obstacle to scaling up the size of quantum systems, that is, the noise from the environment that may perturb a quantum system – a phenomenon termed decoherence (Brooks, 2012). The solution to this problem is called quantum error correction (Preskill, 2018). Quantum error correction requires high overhead in encoding information into an entangled system, making it also difficult to scale. These technical challenges must be addressed before quantum computing can scale. Thus, the technology has a high uncertainty as to its potential impact.

### 3 The challenges of researching and teaching emerging technologies in IS

As discussed previously, IS researchers have not been actively involved in researching and teaching emerging technologies in their early stages. One plausible explanation for this is that IS researchers often lack knowledge of the foundational principles for emerging technologies that often originate from math, computer science, engineering, or the natural sciences.

Again, we use quantum computing as an example. Figure 1 represents a traditional view of how each academic discipline would contribute to quantum computing research were it in wide adoption. In that view, research and development in quantum computing would be conceptualized into five hierarchical layers: theoretical foundations, hardware, system software, application software, and management. Each of the five layers requires a specific set of core disciplinary skills. More specifically, mathematicians and physicists would research theoretical foundations such as superposition, entanglement, and measurement of quantum systems (Brooks, 2012). Electronics and computer engineers would lead quantum computing hardware design such as quantum processor design, physical implementation of qubit encoding and error correction, and qubit scaling (Preskill, 2018). Computer scientists would initiate the design of system software, such as quantum operating systems, quantum compilers, and quantum circuits (Bernhardt, 2019). Both computer scientists and IS researchers would contribute to the design of specific quantum software applications, such as software applications for quantum cryptography, quantum search, and quantum machine learning and optimization. IS researchers and researchers from other business/management disciplines would research management issues related to translating quantum computing applications into economic and strategic values for the organization such as societal impacts of quantum computing and associated ethical considerations, how to select and implement appropriate quantum computing applications, how to manage changes related to quantum computing, and how to manage quantum computing human resources.



**Figure 1. Traditional View of how IS would contribute to Quantum Computing Research**

We argue that this traditional view in Figure 1 limits the potential contributions of IS researchers in emerging technology research. The IS research community has a great potential to contribute to the effective adoption of quantum computing by setting a research agenda that goes beyond management issues and related software applications. To do so, the IS research community must be willing to break its own disciplinary research boundaries and collaborate with other reference disciplines. Such cross-disciplinary collaboration would enrich IS researchers' understanding of the ramifications of design choices made at the lower layers. Once IS researchers begin to understand the theoretical foundations, hardware, and system software layers, they would make informed recommendations regarding issues such as usability, privacy, and security of quantum applications.



Another reason that IS researchers often lack knowledge of the foundational principles for emerging technologies is that IS curricula often lag in introducing these technologies. IS curricula provide a foundational preparation for IS academic research and practice (Topi et al., 2010). Increasingly, the IS community recognizes the importance of emerging technologies in its curriculum. The draft 2020 IS Curriculum identifies emerging technologies as an elective competency area for IS students in the technology/security realm (ACM-AIS IS2020 Taskforce, 2020, p. 25). According to the draft curriculum, the study of emerging technologies promotes “critical thinking and problem solving,” “learning how to learn,” and “high tolerance for ambiguity” (p. 42). The draft also notes that IS graduates benefit from studying emerging technologies through acquiring lucrative employment opportunities as well as “excellent opportunities for establishing small start-ups” (p. 20). Introducing emerging technologies such as quantum computing into curricula can help build these desired capabilities of IS graduates, some of whom may become transformational leaders in information systems and technology.

Yet, such a curriculum change is not an easy task. There are four stages of time lags in curricula changes (see Figure 2): recognition, decision, implementation, and impact (OECD, 2017). In the context of IS education, the recognition lag deals with the time needed to identify future IS workforce demands and changes needed in the current curricula. The decision lag refers to the time needed to organize the planning and decision-making processes to guide the needed IS curricula changes. The implementation lag denotes the time needed to implement the IS curricula changes in practice, and the impact lag signifies the time needed for students to translate the learning experience into practice. The value added is greater when action is taken in the earliest stage.

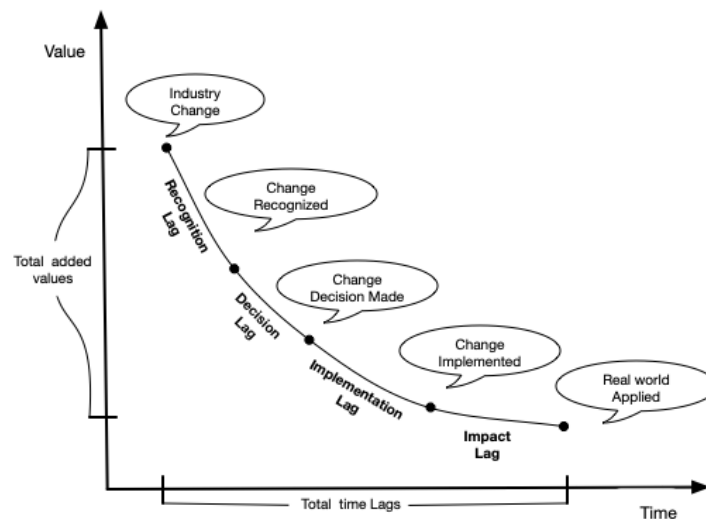


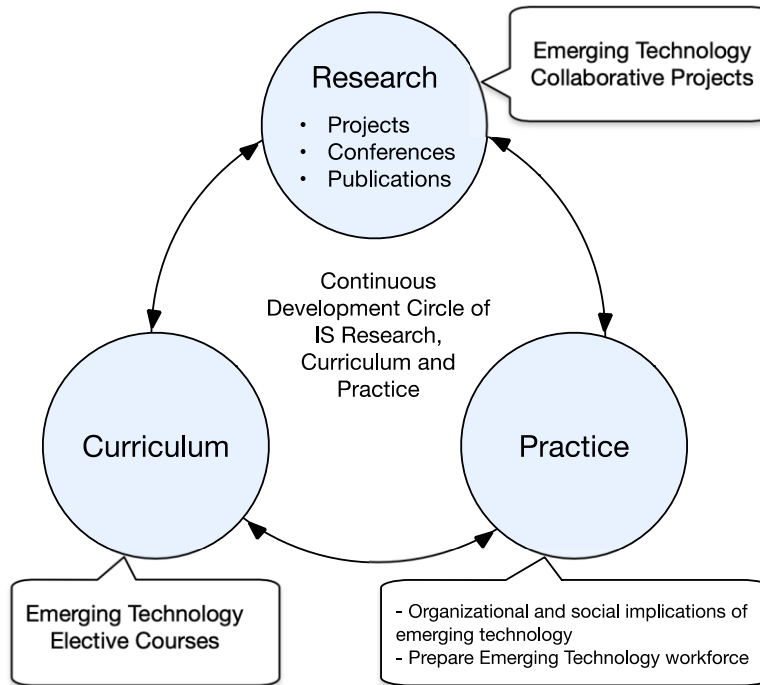
Figure 2. Stages of Time Lags in Curricula Change

We argue that IS needs to act at the earliest stage of curricula change and start introducing emerging technologies before they are massively adopted by industry. To do so, an elective course focusing on foundational principles, applications, and managerial implications of an emerging technology such as quantum computing should be included in IS curricula even though the technology might still be in its emergent phase. Such a course would encourage IS researchers to build expertise in the emerging technology. IS researchers may also collaborate on research projects with scholars from disciplines with the requisite expertise in quantum computing. Collaborative projects of this kind will allow IS researchers to branch out and bring new ideas to IS research.

In the next section, we unpack the above challenges, and present a scholarly agenda for quantum computing in IS.

## 4 A Scholarly Agenda for Quantum Computing in IS

The discussion above highlights research and teaching as two integral aspects of challenges of emerging technologies in IS. As an applied discipline, IS also needs to align research and teaching with practice. Thus, we posit that an IS scholarly agenda for quantum computing, or any other emerging technology, must engage in a continuous development circle of research, curriculum development, and practice.



**Figure 3. The Interplay Among Research, Curriculum Development, and Practice**

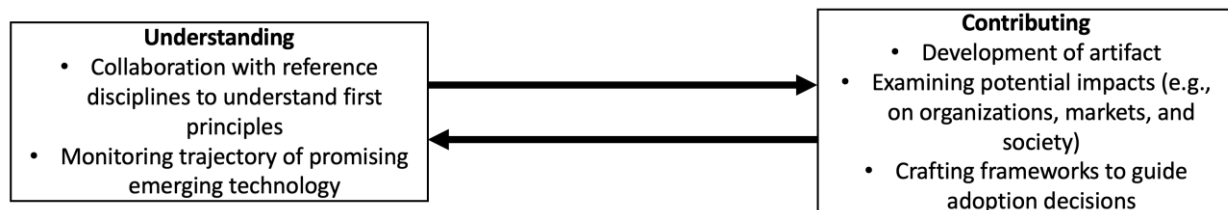
As illustrated in Figure 3, the development circle includes three bidirectional relationships. The research and curriculum relationship indicates that research in emerging technology keeps the curriculum up to date and relevant (i.e., reducing the recognition lag), while teaching the emerging technology in the curriculum allows IS researchers to gather feedback, reflect, and improve upon the research. The research and practice relationship highlights the importance of conducting research that informs practice in industry. Meanwhile, when the industry identifies some challenges with respect to an emerging technology, it can inform the research. The practice and curriculum relationship shows that the practical needs in industry would drive the curriculum development, and at the same time, IS graduates can apply what they have learned about emerging technologies when they join industry. For IS researchers to contribute to research in emerging technologies, we propose three strategies that target research, curriculum development, and practice as shown in Figure 3. They are: (1) starting collaborative projects with colleagues from reference disciplines and industry to build understanding of how best IS can contribute; (2) introducing relevant elective courses early into the curriculum; and (3) collaborative projects with colleagues from industry. For quantum computing, the curriculum  $\square$  practice link can be strengthened by having IS students intern at companies involved in quantum computing. The link can also be strengthened by having students attend industry facilitated workshops on quantum computing e.g., the IBM Summer Schools on Quantum Computing .

Our perspective contrasts with the research of mature technologies with widespread adoption. The research questions thereof can be tackled without need to incorporate curricula changes. Because emerging technologies are characterized by radical novelty, IS researchers need to gain requisite expertise by collaborating with colleagues from other reference disciplines while also creating new courses that teach the foundational principles that underlie these technologies. The ultimate impact of emerging technologies may take some time to be realized or may not even be brought to fruition. Nevertheless, students learning emerging technologies acquire critical thinking abilities and opportunities to apply creativity in unfamiliar contexts, all of which are valuable skills for IS graduates. Guided by the two strategies, we next propose research and teaching agendas for quantum computing in IS.

## 4.1 Research Agenda

In this section, we present several examples of how IS researchers may harness the research opportunities in quantum computing. There are two broad and mutually reinforcing components of the research agenda i.e., (1) understanding the emerging technology and (2) contributing to developing the

technology and examining its potential impact (Figure 4). The understanding phase is integral for emerging technologies owing to their novel character that may require learning foundational principles from disciplines other than IS. Further, monitoring the trajectory of an emerging technology (e.g., changes in adoption rates, technical advances in the development of the technology, and regulatory changes that may implicate the trajectory) furthers understanding of its co-evolution. For the contribution phase, IS researchers would be actively involved in development of the artifact, development of frameworks or guidelines for organizations to decide if or when to adopt the technology, and examining potential impacts of the technology on organizations, markets, and society. Understanding and contributing are mutually reinforcing to the extent that the better an IS researcher understands foundational principles of the technology the better placed they are to contribute to its development and impacts. Sidorova et al. (2008) identified the intellectual core of the IS discipline as comprised by five areas: IT and organizations, IS development, IT and markets, IT and individuals, and IT and groups. Likely, during the emergent phase wherein the technology is not yet in wide adoption, the IT and individuals (subsuming topics such as IT adoption, trust, and individual technology acceptance) and IT and groups (e.g., virtual teams, trust, and collaboration) areas are less relevant than the other areas. Thus, the examples we provide correspond to the IS development, IT and organizations, and IT and markets areas, and are presented as a means to demonstrate how IS researchers could conduct rigorous research in quantum computing even in its emergent phase.



**Figure 4. The Understanding ⇌ Contributing Loop to Guide Research into Emerging Technologies**

#### 4.1.1 Understanding: Collaborating with Other Reference Disciplines

Emerging technologies may initially be invented by disciplines other than IS (e.g., artificial intelligence from math and computer science, blockchain from computer science, and quantum computing from theoretical physics). Rather than waiting until an emerging technology is in widespread use, IS researchers could collaborate with colleagues from other reference disciplines who are “actively creating those future technologies” to understand their underlying concepts, and inquire and discover their sociotechnical ramifications (McGregor & Wetmore, 2009, p. 17). The collaboration may take many forms such as research projects, inviting colleagues as guest speakers in doctoral seminars, keynote sessions, and workshops at IS conferences.

As the conversations with colleagues from these reference disciplines continue, IS researchers could start identifying areas to which they are best able to contribute. The quantum computing workshop held by IBM at the Hawaii International Conference on System Sciences (HICSS) 2020 is an exemplar in this regard. The workshop underscored that advanced cloud platforms for carrying out superposition, entanglement, and measurement of quantum systems already exist, and that IS research may contribute to the evaluation of these platforms’ usability, service variety, and explainability.

#### 4.1.2 Understanding: Monitoring and Embracing Research on Technologies Pre-Widespread Adoption

As discussed earlier, it is generally believed that IS researchers would not be able to lead research in emerging technologies without corresponding data on adoption, use, and impacts of these technologies. The counter arguments to this perception are twofold. First, as discussed earlier, IS researchers may not accurately gauge the progress of an emerging technology because they are not in conversation with their colleagues from other reference disciplines who are actively “creating” these technologies. For example, in quantum computing, many IS researchers are not aware that there are mature cloud platforms with stable user bases, which would support quantum computing experiments. Second, there are other ways of contributing to IS research beyond empirical studies. IS researchers could make theoretical contributions through analysis, explanation and prediction, or through design and action (Gregor, 2006). Neither of these approaches requires data on adoption, use, and impacts.

IS may also contribute to research in quantum computing by creating frameworks and guidelines that describe aspects of adopting quantum computing technology based on industry characteristics and existing knowledge on emerging technology adoption. Further, IS researchers can employ simulations to quantify the potential socio-economic impacts of quantum computing, or prescribe methods, techniques, and principles for constructing prototype (proof-of-concept) quantum applications. Once the potential applications and impacts of quantum computing are understood, organizations may be better informed regarding strategies to respond to the emerging technology.

#### 4.1.3 Contributing to IT and Organizations: Mitigating the Threat to Currently Standardized Cryptography from Quantum Computing

How to mitigate the threat to the security of existing applications from quantum computing is an existing and urgent concern. With Shor's factorization algorithm, a general-purpose quantum computer may break the current cryptosystem (e.g., RSA) for secure data transmission, jeopardizing electronic financial transactions, sensitive government and private company communications, and individual privacy at large. There is a need for quantum-resistant encryption protocols (Marinescu & Marinescu, 2005), and standards-setting organizations in North America and Europe have been working to standardize these protocols (Alléaume et al., 2014). Transitioning existing IT systems from classical to quantum-resistant encryptions will be complex and expensive. IS researchers are uniquely positioned to study how to mitigate the security threats of quantum computing by understanding the nature of the threat, and how different organizations may be prepared for such a transition (Mashatan & Turetken, 2020).

#### 4.1.4 Contributing to IT and Markets: Cultivating Value from Quantum Computing

Microsoft, Google, and IBM, among other top technology companies, have invested heavily in advancing quantum computing out of the theoretical realm into the practical (Dyakonov, 2019). This echoes the first-mover dilemma regarding technology adoption, where some companies may gain competitive advantage from innovating in new technology, and others may gain from following (Suarez & Lanzolla, 2005). Quantum computing represents a potential paradigm shift, and immense advantages may accrue to companies that move to exploit it first. At the same time, quantum computing requires massive costly and uncertain investments, thus, mid-sized organizations that cannot afford these investments might be prudent to wait for others to innovate. How organizations may exploit quantum computing capabilities for strategic value is an important consideration to which IS can contribute.

A further consideration lies in cultivating the different ways of generating business value from quantum computing. Perhaps the value will be generated through the application of quantum AI, which current research suggests may be more accurate than its classical counterparts (Havlíček et al., 2019). The value may also be generated through drastically more efficient optimization algorithms, for example by finance companies in the realms of portfolio optimization, option pricing, and credit risk analysis. Other industries that stand to gain from quantum computing include healthcare, manufacturing, and transportation (Ghose, 2020). IS can contribute by identifying quantum computing applications that would generate business value and communicating these value propositions to different organizations.

### 4.2 Education Agenda

We have presented examples of how IS can contribute to quantum computing research. This requires IS researchers to gain requisite knowledge in quantum computing. A further step is to bring this requisite knowledge into IS curricula before change has already occurred in industry. Introducing quantum computing in IS curricula would prepare future IS researchers to be better positioned in researching quantum computing software applications and management issues. It would prepare future IS managers as to what is possible for quantum computing, and who may be selecting and managing quantum computing platform(s) or quantum-based applications for their organizations. Introducing quantum computing is advantageous not only to build individual foundational competencies (see Table 2) of IS graduates, but to also promote critical thinking and problem solving, lifelong learning and development, and high tolerance of ambiguity.

**Table 2. IS Foundational Competency Areas and Associated Learning Objectives from Studying Quantum Computing**

Competency Area	Learning Objectives	Applicable examples to realize learning objective
IS foundations	Create a business case for introducing quantum computing in an organization.	Creating or maintaining competitive advantage through new business models in quantum computing.
IT infrastructure	Examine available quantum computing infrastructure resources and plan them within an existing IT infrastructure.	Comparing and selecting IBM Qiskit Aqua vs Google's Tensorflow Quantum for different business scenarios.
Secure computing	Discuss the security implications of quantum computing. Formulate a plan to protect legacy systems in a quantum world.	Exploring and evaluating government plans for provably secure or post-quantum cryptography infrastructure.
IS ethics, sustainability, use and implications for society	Discover ethical and sustainable implications of quantum computing.	Examining the implications of a quantum capability gap.
IS management and strategy	Articulate strategic value of quantum computing from an organizational perspective.	Identifying quantum applications that can create value for a given organization.
Digital innovation	Identify opportunities for digital innovations in quantum applications across different industries.	Quantum optimization of investment portfolios, credit risk analysis for finance, quantum AI in technology organizations.

We propose introducing an elective quantum computing course in IS curricula. Such an elective course should explore the basics of quantum computing so that IS students can “articulate and critically reflect on the unique features” (ACM-AIS IS2020 Taskforce, 2020, p. 53) of the technology. The prerequisites for the course would be limited to a basic understanding of linear algebra and knowledge of an object oriented programming language. IBM, arguably the company with the best instructional material on quantum computing, states their prerequisites for an introductory class as follows: “[m]inimal prerequisites are required for the Qiskit Global Summer School. If you know how to multiply two matrices, and have some programming experience in Python, you are ready...” . Appendix A presents a short tutorial on quantum computing basics. As shown earlier in Figure 1, IS plays a central role in the application and management layers of quantum computing research. The elective course should also expose students to the new and potential quantum computing applications and their related managerial impact. We detail quantum computing applications that can enhance existing business systems in Appendix B.

## 5 Conclusion

The main contribution of this paper is to advance a scholarly agenda for IS to overcome challenges in teaching and researching emerging technologies like quantum computing. Collaboration with counterparts from math, physics, computer science, and engineering disciplines to better understand the foundational principles and ramifications of emerging technologies forms a bedrock of such an agenda. We also contribute towards IS research at large by proposing alternative ways to think about doing research in the perceived absence of associated data on adoption, use, and impacts. Our recommendations on incorporating quantum computing as an elective course in IS curricula are congruent with the proposed requirement for IS graduates to develop core IS competencies and prepare them to become transformational leaders in emerging technologies. As IS scholars actively embrace research on emerging technologies, they can become leaders in innovation by identifying newfangled opportunities afforded by the technologies. When students are exposed to emerging technologies, they can hone innovation skills, which practically empower them to (1) make the business case for or against adopting a given emerging technology in an organization and/or (2) transform existing business practices or even entire industries by leveraging the radical novelties stemming from emerging technologies. Indeed, a stronger embrace of

research on emerging technologies helps IS maintain relevance with the evolving needs of industry and thus propels the IS discipline forward. We hope that this paper spurs interest and further scholarship in quantum computing and other emerging technologies among the IS community.



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## Appendix A: Basics of Quantum Computing

In computing systems, information is encoded in states. The higher the number of states a computational system can store, the greater its information capacity (Marinescu & Marinescu, 2005). In contrast to classical computing, quantum computing systems can simultaneously be in multiple states by their properties of superposition and entanglement, meaning that they theoretically have higher information capacity for the equivalent number of classical bits. A classical bit encodes information as either a 0 or 1. Thus, at any moment, each bit is in a state 0 or 1, and this state arises out of the voltage level of the bit, e.g., 3 volts might mean state 1, and 0 volts state 0. By combining multiple bits, one can encode bigger numbers or text characters, e.g., 8 bits can encode the integers 0 to 255 ( $2^8 - 1$ ), and ASCII can encode 128 characters, based on 7 bits.

### Superposition

The qubit, in contrast, utilizes the rules of quantum mechanics. For example, in an atom, a given electron may be in one of three spin states: up, down, or a combination of up and down (a phenomenon known as superposition) (Brooks, 2012). There are properties other than spin states that give rise to different states in quantum systems, e.g., polarization of photons and orbital state of electrons in atoms. Thus, in contrast to the classical bit, the qubit may be in multiple states at a single time instance. One could then define a qubit as a unit capable of storing a single state or a superposition of possible states. Consider a quantum system where information is encoded by the orbital state of an electron, say in the hydrogen atom (see Figure A1). The electron can be in level 0 or 1, or, simultaneously in levels 0 and 1. The electron does not inhabit the region between 0 and 1, rather the energy levels are quantized, only values of 0 and 1 are allowable.

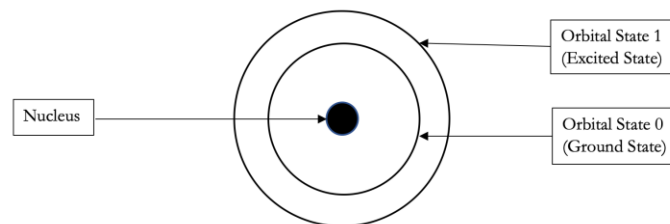


Figure A1. Hydrogen Atom with Two Energy Levels

### Measurement

Measurement forms a key principle of quantum systems. In classical systems, when measurements are taken, they do not affect the system in question. For example, measuring the speed of a car using a speedometer does not affect its speed, or at least the effect is so small as to be negligible. In quantum systems, however, measurements affect the state of the system. Quantum systems consist of very small particles, and measuring the system using photons (which are of similar size), for example, perturbs the system; thus, the measurement effect is noticeable, significant, and part of the underlying theory (Bernhardt, 2019). However, the measurement effect also matters with regards to its type, such that when measurement of a quantum system is carried out in two different bases, the outcome may be predicted in one of the bases, but random in the other.

### Entanglement

Another defining principle of quantum systems is the phenomenon of entanglement, i.e., getting two qubits to interact with each other so that their states become strongly correlated (Couteau, 2018). With two entangled qubits, it becomes possible to simultaneously encode 0 (00), 1 (01), 2 (10), and 3 (11) in the quantum system. Entangled qubits lose their independence, and it becomes impossible to describe their individual states independent of the state of the complete quantum system. When measuring the system, a qubit falls into state 0 or 1 with some probability. At the same time, the state of the entangled qubit also changes according to the correlation of the entanglement.

## Appendix B: Applications of Quantum Computing

The research area of quantum algorithms and applications has gained momentum over the past two decades. Below we list some examples of these quantum algorithms and applications.

### Integer factorization

An example of an algorithm that exhibits quantum speedup is the integer factorization algorithm that finds the prime factors of a given integer  $N$ . The best classical algorithm for integer factorization runs in exponential time. The quantum algorithm of Peter Shor (1999) solves this problem substantively faster in polynomial time  $O(\log N)^3$ . However, Shor's algorithm implies that the RSA public-key cryptosystem<sup>1</sup>, a standard cryptographic algorithm on the Internet based on prime factorization complexity (Rivest et al., 1978), is insecure against the attack of a quantum computer with enough qubits.

### Quantum Search

A basic problem in computer science is the unstructured search problem: given  $N$  allowed inputs, find one input with a corresponding output of 1, and for all other inputs, the corresponding output is 0. A classical exhaustive search algorithm solves this problem using linear time  $O(N)$ , while Grover's (Grover, 1997) quantum algorithm solves it much faster in logarithmic time. Applications of Grover's algorithm include determining graph connectivity, pattern matching in text processing and bioinformatics, and spatial search (Montanaro, 2016).

### Quantum Walks

A random walk is a stochastic process that describes a path with a sequence of random steps in some mathematical space. Markov Chain Monte Carlo (MCMC), a special one-dimension random walk application, is a powerful method for the simulation of stochastic processes with probability density proportional to a known function (Geyer, 1992). MCMC algorithms are often applied to searching and sampling problems, such as selecting a random page on the Internet. The quantum counterparts of classical random walks are quantum walks that simulate the quantum evolution of an object transitioning between quantum states. Similar to classical random walks, there are two types of quantum walks: discrete quantum walks that are constrained in discrete time steps and continuous quantum walks with no timing restrictions at all (Venegas-Andraca, 2012). Just as random walks have been successfully adapted to develop classical computation algorithms, quantum walks provide a similarly powerful and general framework for building fast quantum algorithms (Venegas-Andraca, 2012).

### Quantum cryptography

Classical cryptography is mainly implemented by asymmetric distribution of keys between two actors, conventionally named Alice and Bob (Rivest et al., 1978), followed by the use of symmetric cryptography to encrypt the confidential content under the distributed keys. In this cryptographic scheme, if Alice intends to send a message to Bob, she first sends a request for a public key from Bob, which she will use to encrypt her message. Bob (and only Bob) will have the ability to decrypt the message, because his private key is mathematically related to the public key used by Alice to encrypt the message. The parameter sizes, e.g., key sizes, are chosen appropriately so that deriving the private key from the public key is computationally infeasible; thus, eavesdroppers with access to the public key are unable to intercept the messages through solving the integer factorization problem with classical computing. However, with quantum-integer factorization algorithms, a quantum computer with enough qubits would solve the problem much faster. This means that existing systems may be rendered insecure as soon as quantum computing is practical (Lomonaco, 2000). Thus, quantum technology is a threat to the security of existing cryptography systems.

At the same time, quantum technology presents a possible new form of cryptography, one that relies on the secure exchange of encryption keys between two parties. This approach is known as quantum key distribution (QKD). BB84 is an example of a QKD schema, building on the quantum property that when a quantum system is measured, its state also changes. When an eavesdropper listens to conversations

<sup>1</sup> RSA is a cryptographic scheme invented by Rivest, Shamir, and Adleman (1978).

using the BB84, the information being transmitted will be changed, making it easy to detect that such eavesdropping is taking place (Bennett & Brassard, 2014) .

## Quantum machine learning

Machine learning entails finding hidden patterns in data. Historically, advances in computing power have allowed progressively more advanced machine learning algorithms to be implemented, e.g., neural networks and support vector machines (Biamonte et al., 2017). For certain problems, quantum algorithms can outperform their classical algorithm equivalents, a phenomenon called quantum speedup. Grover's algorithm, discussed above, is an example of quantum speedup in search and optimization. Many of the components underlying machine learning algorithms potentially exhibit quantum speedup, offering great promise in improving the algorithms' performance.

A key component of machine learning algorithms that can benefit from quantum speedup is feature mapping, i.e., projecting training data onto high-dimension vector spaces. For example, when detecting objects from a given image, one might break the image into pixels and classify each pixel by an RGB value. With quantum computing, the possible vector spaces are exponentially larger than those of classical computers, meaning that quantum machine learning can better disentangle the effects of specific features on a given objective function (Havlíček et al., 2019). Another component of machine learning, matrix multiplication, can be solved exponentially faster using quantum algorithms compared to the best-known classical algorithms (Harrow & Montanaro, 2017). For support vector machines and perceptron-based neural networks, quantum algorithms will be able to find the best separating hyperplane between classes of data points much faster than their classical counterparts will. Similarly, pattern matching also exhibits quantum speedup (Ramesh & Vinay, 2003). Therefore, with quantum computing, many machine learning algorithms (e.g., principal component analysis, least squares regression, support vector machines, and neural networks) can exhibit much better performance in terms of speed and classification accuracy.



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