NATIONAL ARCHIVES

OFFICE of the CHIEF RECORDS OFFICER

Quantum Information Science and Technology

Implications for Records Management

White Paper

National Archives and Records Administration

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Introduction

The National Archives and Records Administration, Office of the Chief Records Officer for the U.S. Government, has been researching and writing about emerging technologies that will have an impact on the field of records management. This is the third in a series of white papers—the first one being Blockchain (2019) and the second, Cognitive Technologies (2020). Unlike previous white papers in which the technologies were more established, the field of Quantum Information Science and Technology (QIST) is in its early stages, so the technological impacts for records management are evolving.

This white paper is intended to provide a non-technical introduction to QIST for federal records managers. Emerging quantum technologies could have the biggest impact in these areas of records management: cryptography, authentication, encrypted communication, storage of records, and records retrieval. Records managers may find this information helpful as the technology evolves and matures.

Quantum Information Science and Technology (QIST)

QIST is the merger of quantum physics and information theory. Quantum physics describes nature at an atomic and subatomic level. Information theory is the study of quantification, storage, and communication of information *(A Federal Vision for Quantum Information Science,* 2009). Early examples of quantum technologies are lasers, transistors, magnetic resonance spectroscopy, and atomic clocks. These, in turn, gave us computers, the internet, medical imaging, and GPS navigation *(A Coordinated Approach to Quantum Networking Research,* 2021). Future technologies such as quantum computers, quantum networks, and quantum sensors are being researched and developed by combining quantum physics and information theory.

U.S. Federal Government Support for Basic Research
Since its founding, the United States has encouraged scientific creativity and exploration. Our Constitution reflects this and grants Congress the power "to promote the progress of science and useful arts" (U.S. Constitution, Art. 1, sec. 8). Early government support for research can be seen in the 1862 Morrill Land-Grant College Act, which authorized public land grants for colleges to teach agriculture and mechanical arts. Several years later, the 1887 Hatch Experiment Station Act provided federal grants to states for agricultural experimentation.

The combination of the Great Depression and both world wars spurred active government interest in solving social, economic, and military problems. The Office of Scientific Research and Development (OSRD) was established by President Roosevelt to support America's efforts in the war. OSRD director Vannevar Bush wrote a report to President Roosevelt titled "Science: The Endless Frontier," arguing that “basic research is the pacemaker of technological progress.” Bush’s report along with John R. Steelman’s report to President Truman, "Science and Public Policy: A Program for the Nation," helped to establish the National Science Foundation (NSF) in 1950. As physicist William A. Blanpied noted, “What made the NSF so different from the outset was its emphasis on government policy in support of scientific activity, not science for government policy.” By establishing the Office of Science and Technology Policy in the Executive Office of the President in 1976, Congress recognized the need for the President to receive “advice on the scientific, engineering, and technological aspects of issues that require attention at the highest levels of Government.”

The federal government has a unique role in funding long-term basic research that may have the potential for practical application. One example of the lengthy timeline is the Department of Defense’s ARPANET (Advanced Research Projects Agency Network). This project was proposed to make links between computers at different physical locations to ensure continuity of communications during the Cold War. Oftentimes, the benefits and advances from basic research investments were unanticipated. For example, what began as a computer-to-computer signal in 1969 eventually led to the development of mesh networks, packet transmission protocols, and the internet. The NSF funded the network for more than 10 years before the commercial capabilities became clear. ARPANET was decommissioned in 1990 after the telecommunication and computer industries expanded the network for commercial use (DARPA).

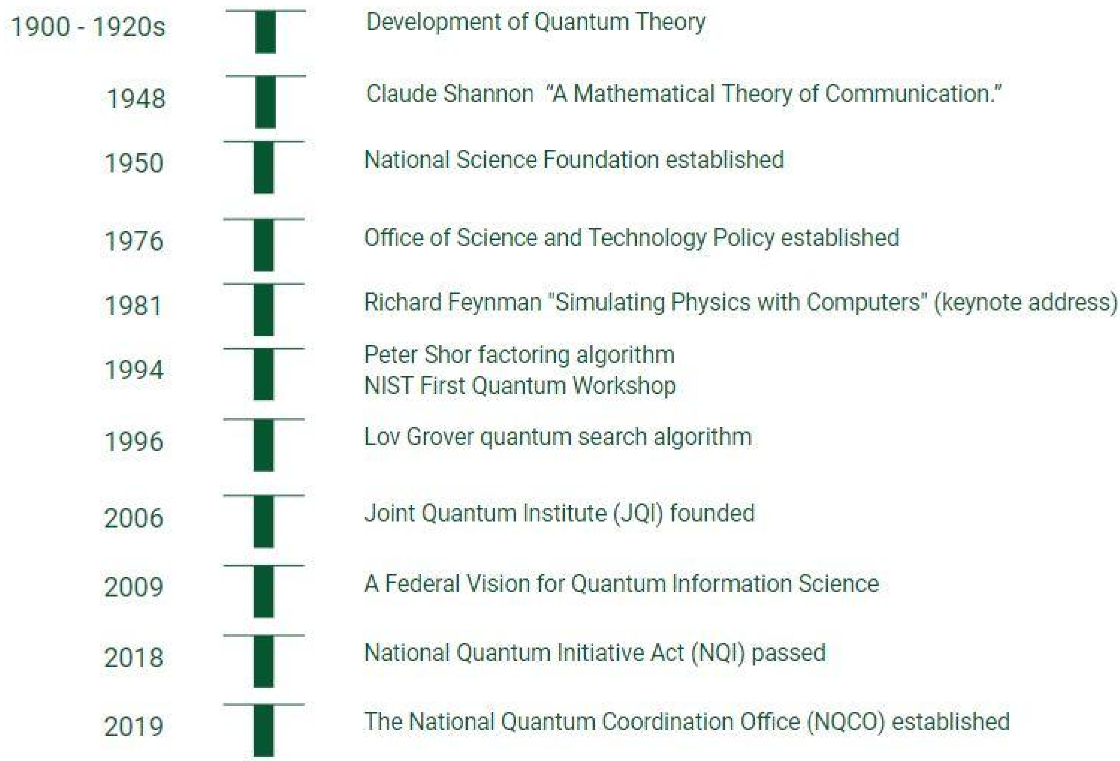
Like those who worked on the early internet, today’s researchers are still exploring the capabilities of QIST. In 1981, physicist Richard Feynman suggested building computers based upon the principles of quantum mechanics because of the difficulties of simulating quantum mechanical systems on classical computers. In 1994, applied mathematician Peter Shor, proposed a quantum computer algorithm that would theoretically factor large numbers. As Shor’s algorithm gained understanding in the scientific community, the National Institute of Standards and Technology (NIST) hosted the first workshop focused on quantum computing and communication in 1994. The following year, researchers at NIST experimentally realized the first quantum logic gate.[1] Over the next decade, several agencies from across the federal government began funding academic research into quantum information science, such as the creation of the Joint Quantum Institute (JQI) in 2006. The National Science and Technology Council's (NSTC) Subcommittee on Quantum Information Science issued a report in 2009, *A Federal Vision for Quantum Information Science.* This vision document led to workshops and collaborations between the federal government, academia, and industry.

In 2016, NSTC issued a report on the challenges and opportunities around quantum information science, and the White House Office of Science and Technology Policy convened a forum on quantum information science. The following year, the National Photonics Initiative—an alliance of government, academia, and industry—shared a proposal, "Call for the National Quantum Initiative," with Congress. In September 2018, the NSTC's Subcommittee on Quantum Information Science released the *National Strategic Overview for Quantum Information Science,* which emphasized goals for research, workforce expansion, and coordination between government, academia, and industry (Raymer, 2019). Later that year, on December 21, the President signed the National Quantum Initiative Act (NQI).

The purpose of the NQI was to accelerate U.S. leadership in quantum information science for economic prosperity and national security. The National Quantum Coordination Office (NQCO) was established within the White House Office of Science and Technology Policy to foster a whole-of-government approach to quantum information science. NQCO serves as the primary point of contact for federal quantum science and technology activities and disseminates findings and recommendations. Executive Order 13885 established the National Quantum Initiative Advisory Committee in 2019, and this committee includes representatives from federal agencies, industry, and academia (Raymer, 2019). Executive Order 14073 in 2022 enhanced the advisory committee by establishing it as a presidential advisory committee. Currently, a number of government agencies and national laboratories have research efforts in quantum information science, including the National Security Agency, the Intelligence Advanced Research Projects Activity, the Defense Advanced Research Projects Agency, the National Science Foundation, the National Institute of Standards and Technology, the

[1] Logic gates, which allow or block electricity, are building blocks for processing information. By arranging gates in a circuit, engineers enable computers to carry out multiple mathematical calculations. Unlike classical logic gates, quantum logic gates can process multiple possibilities simultaneously (NIST "Quantum Logic Gates").

Department of Energy, the Army Research Laboratory, the Air Force Research Laboratory, and the Naval Research Laboratory.



Classical and Quantum Computing

Classical computing is based on the binary digit or bit, which is the most basic way to store information in a computer. A bit is represented as either a 0 or 1 and can be thought of as a binary set, such as the Boolean result true/false. More complex processing can be accomplished by stringing bits together into bytes and larger configurations. The processing of bits occurs in central processing units (CPUs), which sequentially process code. Advances over the past decades such as increased CPU processing speed, parallel CPU cores, and the development of graphics processing units have dramatically improved the speed at which a computer can execute calculations (Rupp, 2018). The purpose of all these advances was to make the processing of binary 0s and 1s faster and more efficient.

Quantum computers use 0s and 1s to process data, but rather than using only discrete states like 0 and 1, the state of a quantum bit or qubit can be a combination of 0 and 1 simultaneously (Nielson 2010). This is known as superposition. Multiple qubits can be correlated through entanglement. Entanglement means that the qubits are linked in such a way that measuring one qubit will instantaneously collapse the other entangled qubits (Mooney, 2019). Using superposition and entanglement, a quantum computer can solve certain problems faster than a classical computer. Quantum states are very sensitive to their environment. When unaccounted for, unwanted thermal, optical, or mechanical interference can cause a superposition to collapse, ultimately limiting computational capabilities.

How a classical computer and a quantum computer approach a computational challenge might illuminate the differences more clearly. Many current computers have 64 bits of processing, which means that there are approximately 1.8×10^{19} different combinations of 0 and 1 across the 64 bits. A 3.1 GHz processor can process 64 bits 3.1 billion times a second. At that speed, it would take almost 189 years for a computer to try all of the combinations of 0 and 1 across 64 bits. Conversely, a quantum computer with 64 qubits can be in a superposition of all combinations of 64 bits, and if the superposition can be quickly altered to highlight the correct answer while suppressing the incorrect answers, the quantum computer can compute faster. In 2019, a team at Google used a 53-qubit quantum computer to complete a computation in 200 seconds that, at the time, would take a state-of-the-art classical computer approximately 10,000 years (Arute, 2019).

Quantum Advantage Over Classical Computers

There are a number of examples where quantum computing could have an advantage over a classical computer. Three of the most significant are:

(1) **Factoring:** Using Peter Shor's factoring algorithm, quantum computers could extract the private key for RSA messages much more quickly than classical computers (Raymer, 2019).

(2) **Quantum Search:** In 1995, Lov Grover demonstrated the potential of quantum computers to search through unstructured data. Grover's algorithm showed how quantum computers could speed up and expand search capabilities (Nielson, 2010).

(3) **Quantum Modeling:** The third area was suggested by Richard Feynman in the early 1980s and allows scientists to model complex quantum systems in a computer that is itself a complex quantum system (Feynman, 1982).

Developing Quantum Computers

NIST's 1994 workshop was the first workshop in the field. It brought together physicists, mathematicians, and computer scientists from academia, government, industry, and the intelligence community. The event included a talk by co-organizer Artur Ekert, a physicist at the University of Oxford, who was well known among quantum physicists. His talk inspired theoretical physicists Ignacio Cirac and Peter Zoller of the University of Innsbruck to envision making quantum computers a reality in the laboratory.

> Researchers would trap a group of individual ions in a line, like birds on a wire. Lasers would manipulate the ions' energy states so that they each represented 0s and 1s or superpositions of the two. Each ion would communicate with another by rocking back and forth. The rocking would enable each ion to exchange information with its neighbors. In this way, researchers would be able to carry out computations with the qubits ("NIST Jump-Starts," 2018).

Around the same time period, Dave Wineland with NIST was working on making a more accurate atomic clock using ions. When Wineland and colleagues saw Cirac and Zoller's paper, they immediately recognized parallels between controlling atoms in an atomic clock and performing quantum computation. At the end of 1995, Wineland and his team announced the first operation on a qubit. Wineland's research would be recognized in 2012 with a Nobel Prize for his work in experimental methods that enable measuring and manipulating individual quantum systems ("NIST Jump-Starts," 2018).

The first quantum computer, built in 1998, was a very rudimentary computer consisting of just two qubits and only operated for a few nanoseconds due to the fragility of the qubits to external interference. In 2000, two competing projects announced that they had created quantum computers with four and seven qubits, but external interference again limited their size and usefulness. While these projects demonstrated the possibility of quantum computing, they were far from being scaled for any practical application (Holton, 2021). Over the last decade a number of companies have begun investing in quantum computing with the goal of overcoming the external interference that affects qubits. The field is still evolving with multiple approaches for quantum computing being developed as illustrated in the figure below.

A bit of the action

In the race to build a quantum computer, companies are pursuing many types of quantum bits, or qubits, each with its own strengths and weaknesses.

	Superconducting loops	Trapped ions	Silicon quantum dots	Topological qubits	Diamond vacancies
	A resistance-free current oscillates back and forth around a circuit loop. An injected microwave signal excites the current into super-position states.	Electrically charged atoms, or ions, have quantum energies that depend on the location of electrons. Tuned lasers cool and trap the ions, and put them in superposition states.	These "artificial atoms" are made by adding an electron to a small piece of pure silicon. Microwaves control the electron's quantum state.	Quasiparticles can be seen in the behavior of electrons channeled through semi-conductor structures.Their braided paths can encode quantum information.	A nitrogen atom and a vacancy add an electron to a diamond lattice. Its quantum spin state, along with those of nearby carbon nuclei, can be controlled with light.
Longevity (seconds)	0.00005	>1000	0.03	N/A	10
Logic success rate	99.4%	99.9%	~99%	N/A	99.2%
Number entangled	9	14	2	N/A	6

(Popkin, 2016)

QIST Challenges

While there is great potential in QIST, additional factors are complicating the shift from quantum research to quantum computing. The fragility of qubits often requires a very cold environment to maintain the quantum state and limit external interference. Maintaining extremely low temperatures for quantum computing requires high levels of energy consumption. Despite this, a quantum computer may use less energy overall to solve problems that would take much longer on a classical computer. In addition to the technical challenges, the field has a shortage of workforce talent. NSTC's 2022 strategic plan on workforce development notes that "[b]eyond the significant technical challenges facing QIST research and development (R&D), the shortage of talent constrains progress. The field is currently creating more job openings than can be filled, with the variety of jobs related to QIST expanding in academia, industry, national labs, and government" (QIST Workforce National Strategic Plan, 2022).

QIST Implications for Records Management

Quantum computing poses challenges beyond technologies based on classical computation because it is based upon superposition and entanglement, which do not have classical counterparts. For records management, this creates a unique set of challenges that differ from other emerging areas like blockchain and artificial intelligence. As with any evolving field, there are future implications that we will not be able to predict. Below we have highlighted a few areas for records management experts to track.

Cryptography is used to protect information and digital identity authentication. Some current public key cryptography is based on the length of time it takes a classical computer to factor large numbers. If it takes 30 years using classical computers to factor a large number, then cryptography can effectively protect information for that period of time. As explained above, Shor's algorithm outlines a way for a quantum computer to factor a large number much faster than a classical computer. Records managers will contend with the reality that encrypted information and digital identities will be more vulnerable to attack by quantum computers. The federal government has identified this risk, and many agencies, including NIST, the National Security Agency (NSA), and Department of Homeland Security, are developing quantum-resistant or post-quantum cryptography that can use existing infrastructure.[2]

In general, interference can cause delicate quantum states to collapse. This sensitivity presents two related challenges for a records manager. First, a qubit cannot currently be stored for more than a microsecond. It would be challenging to retain a record that has a quantum component, and therefore a quantum computer would likely never hold the final version of a record. Second, records encoded using superposition cannot be duplicated because the act of copying the records would cause the superposition to collapse and thereby cause a change in the record (Wooters, 1982). Agencies will likely use a quantum computer for a specific task, such as processing, calculating, or searching, and then capture the output in a classical format. For example, a quantum computer might be used to search unstructured data, but the output of the search would be used by a classical computer. The records generated by quantum processing are likely intermediary records as defined in General Records Schedule 5.2, meaning that they are created or used in the process of creating a subsequent record. If the quantum computer's sole function is to receive and process data from other classical systems, it is essentially a "pass-through" system.

[2] Theories suggest that quantum key distribution (QKD) or quantum cryptography (QC) allows detection of the presence of an eavesdropper, (which is not a feature not provided in standard cryptography); however, QKD requires a quantum network. NSA is recommending focusing on quantum-resistant classical cryptographic solutions as more cost-effective and easier to maintain, instead of building a quantum network.

Conclusion

In the near term, classical computers will continue to dominate the marketplace. Given the specialized equipment, space, and expertise required for building and using them, quantum computers will be limited to specific institutions and uses. Technology companies are beginning to address this limitation by making quantum capabilities and services available through the cloud, thereby making these capabilities broadly available to government, academia, and industry and ensuring continued interest and development.

The ability for quantum computers to quickly factor large numbers will be disruptive to the field of cryptography. This change will require a shift from current cryptography standards to systems that are challenging for quantum computers to break.

QIST is in its early days, but with ongoing government, academic, and industry research, QIST will impact our work and lives. In the field of records management, QIST will provide both solutions and challenges. As records managers it is important to be aware of developments in QIST so our profession can evolve to take advantage of quantum system analysis as part of the information landscape.

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