Key Concepts for Future QIS Learners

Background and Overview

On behalf of the Interagency Working Group on Workforce, Industry and Infrastructure, under the NSTC Subcommittee on Quantum Information Science (QIS), the National Science Foundation invited 25 researchers and educators to come together to deliberate on defining a core set of key concepts for future QIS learners that could provide a starting point for further curricular and educator development activities. The deliberative group included university and industry researchers, secondary school and college educators, and representatives from educational and professional organizations.

The workshop participants focused on identifying concepts that could, with additional supporting resources, help prepare secondary school students to engage with QIS and provide possible pathways for broader public engagement. This workshop report identifies a set of nine Key Concepts. Each Concept is introduced with a concise overall statement, followed by a few important fundamentals. Connections to current and future technologies are included, providing relevance and context. The first Key Concept defines the field as a whole. Concepts 2-6 introduce ideas that are necessary for building an understanding of quantum information science and its applications. Concepts 7-9 provide short explanations of critical areas of study within QIS: quantum computing, quantum communication and quantum sensing. The Key Concepts are not intended to be an introductory guide to quantum information science, but rather provide a framework for future expansion and adaptation for students at different levels in computer science, mathematics, physics, and chemistry courses. As such, it is expected that educators and other community stakeholders may not yet have a working knowledge of content covered in the Key Concepts.

The *Key Concepts for Future QIS Learners* workshop was to have taken place at Harvard University in March 2020, hosted by the NSF Center for Integrated Quantum Materials (CIQM); however, in response to the emergence of the COVID-19 pandemic, it was reconceived as a virtual workshop that took place over a span of three weeks, followed by several weeks of reporting, editing, reviewing and consolidation by a core team of workshop leaders. The workshop report reflects this activity and is offered here as a working paper for further discussion and development. The report is not a consensus document, but rather a curated rendering of input from many contributors, attuned to the goals of the Interagency Working Group.

List of Workshop Participants

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Introduction

Quantum information science (QIS) is an exciting field that draws from information theory, computer science, and quantum mechanics to process information in fundamentally new ways. Quantum mechanics emerged in the 1920s to describe certain puzzling behaviors of elementary constituents of matter and light. It revolutionized physics and chemistry and led to inventions like the transistor, laser, and GPS. Subsequently, we came to understand that information itself can be acquired, encoded, and manipulated in quantum systems, giving birth to the new field of quantum information science. Quantum information scientists draw on the work of physicists, computer scientists, and mathematicians, as well as materials scientists, chemists, and engineers. Cross-disciplinary teams are applying QIS to new quantum technologies in communications, networking, data security, navigation, and medical diagnostics. They are also making headway in developing quantum computing systems that may allow us to tackle challenges previously out of reach, in areas such as cryptography, logistics optimization, and across the natural sciences. As with many emerging technologies, quantum information science will likely affect how we live and work and may lead to new developments in broader aspects of society, such as commerce, governance, privacy, employment, and education.

Nine Key Concepts for Future QIS Learners

1. **Quantum information science** (QIS) exploits quantum principles to transform how information is acquired, encoded, manipulated, and applied. Quantum information science encompasses quantum computing, quantum communication, and quantum sensing, and spurs other advances in science and technology.
2. **A quantum state** is a mathematical representation of a physical system, such as an atom, and provides the basis for processing quantum information.
3. Quantum applications are designed to carefully manipulate fragile quantum systems without observation to increase the probability that the final **measurement** will provide the intended result.
4. **The quantum bit, or qubit,** is the fundamental unit of quantum information, and is encoded in a physical system, such as polarization states of light, energy states of an atom, or spin states of an electron.
5. **Entanglement,** an inseparable relationship between multiple qubits, is a key property of quantum systems necessary for obtaining a quantum advantage in most QIS applications.
6. For quantum information applications to be successfully completed, fragile quantum states must be preserved, or kept **coherent**.
7. **Quantum computers**, which use qubits and quantum operations, will solve certain complex computational problems more efficiently than classical computers.
8. **Quantum communication** uses entanglement or a transmission channel, such as optical fiber, to transfer quantum information between different locations.
9. **Quantum sensing** uses quantum states to detect and measure physical properties with the highest precision allowed by quantum mechanics.

Key Concepts with Supporting Fundamentals

1. **Quantum information science** (QIS) exploits quantum principles to transform how information is acquired, encoded, manipulated, and applied. Quantum information science encompasses quantum computing, quantum communication, and quantum sensing, and spurs other advances in science and technology.
   a. Quantum information science employs quantum mechanics, a well-tested theory that uses the mathematics of probability, vectors, algebra, trigonometry, complex numbers, and linear transformations to describe the physical world.
   b. Quantum information science combines information theory and computer science, following the laws of quantum mechanics, to process information in fundamentally new ways.
   c. Quantum information science has already produced and enhanced high-impact technologies such as the Global Positioning System (GPS), which depends on the extreme precision of atomic clocks based on the quantum states of atoms.

2. **A quantum state** is a mathematical representation of a physical system, such as an atom, and provides the basis for processing quantum information.
   a. Quantum states are represented by directions or vectors in an abstract space.
   b. The direction of the quantum state vector determines the probabilities of all of the possible outcomes of a set of measurements. Quantum manipulations in the physical world follow vector operations, incorporating complex numbers and negative values. This captures a behavior of physical quantum systems that cannot be described solely by the arithmetic of probability.
   c. Quantum systems are fragile. For instance, measurement almost always disturbs a quantum system in a way that cannot be ignored. This fragility influences the design of computational algorithms and communication and sensing protocols.

3. Quantum applications are designed to carefully manipulate fragile quantum systems without observation to increase the probability that the final **measurement** will provide the intended result.
   a. A measurement is an interaction with the quantum system that transforms a state with multiple possible outcomes into a "collapsed" state that now has only one outcome: the measured outcome.
   b. A quantum state determines the probability of the outcome of a single quantum measurement, but one outcome rarely reveals complete information about the system.
   c. Repeated measurements on identically prepared quantum systems are required to determine more complete information about the state.
   d. Because of the limitations of quantum measurement (providing only partial information and disturbing the system), quantum states cannot be copied or duplicated.

4. **The quantum bit, or qubit,** is the fundamental unit of quantum information, and is encoded in a physical system, such as polarization states of light, energy states of an atom, or spin states of an electron.
   a. Unlike a classical bit, each qubit can represent information in a **superposition,** or vector sum that incorporates two mutually exclusive quantum states.
   b. At a particular moment in time, a set of n classical bits can exist in only one of 2^n possible states, but a set of n qubits can exist in a superposition of all of these states. This capability allows quantum information to be stored and processed in ways that would be difficult or impossible to do classically.

      c.   Multiple qubits can also be **entangled,** where the measurement outcome of one qubit is correlated with the measurement outcomes of the others.

5. **Entanglement,** an inseparable relationship between multiple qubits, is a key property of quantum systems necessary for obtaining a quantum advantage in most QIS applications.

      a.   When multiple quantum systems in superposition are entangled, their measurement outcomes are correlated. Entanglement can cause correlations that are different from what is possible in a classical system.

      b.   An entangled quantum system of multiple qubits cannot be described solely by specifying an individual quantum state for each qubit.

      c.   Quantum technologies rely on entanglement in different ways. When a fragile entangled state is maintained, a computational advantage can be realized. The extreme sensitivity of entangled states, however, can enhance sensing and communication.

6. For quantum information applications to be successfully completed, fragile quantum states must be preserved, or kept **coherent**.

      a.   **Decoherence** erodes superposition and entanglement through undesired interaction with the surrounding environment. Uncontrolled radiation, including light, vibration, heat, or magnetic fields, can all cause decoherence.

      b.   Some types of qubits are inherently isolated, whereas others require carefully-engineered materials to maintain their coherence.

      c.   High decoherence rates limit the length and complexity of quantum computations; implementing methods that correct errors can mitigate this issue.

7. **Quantum computers**, which use qubits and quantum operations, will solve certain complex computational problems more efficiently than classical computers.

      a.   Qubits can represent information compactly; more information can be stored and processed using 100 qubits than with the largest conceivable classical supercomputer.

      b.   Quantum data can be kept in a superposition of exponentially many classical states during processing, giving quantum computers a significant speed advantage for certain computations such as factoring large numbers (exponential speed-up) and performing searches (quadratic speed-up). However, there is no speed advantage for many other types of computations.

      c.   A fault-tolerant quantum computer corrects all errors that occur during quantum computation, including those arising from decoherence, but error correction requires significantly more resources than the original computation.

8. **Quantum communication** uses entanglement or a transmission channel, such as optical fiber, to transfer quantum information between different locations.

      a.   Quantum teleportation is a protocol that uses entanglement to destroy quantum information at one location and recreate it at a second site, without transferring physical qubits.

      b.   Quantum cryptography enhances privacy based on quantum physics principles and cannot be circumvented. Due to the fragility of quantum systems, an eavesdropper's interloping measurement will almost always be detected.

9. **Quantum sensing** uses quantum states to detect and measure physical properties with the highest precision allowed by quantum mechanics.
    a. The Heisenberg uncertainty principle describes a fundamental limit in simultaneously measuring two specific, separate attributes. "Squeezing" deliberately sacrifices the certainty of measuring one attribute in order to achieve higher precision in measuring the other attribute; for example, squeezing is used in LIGO to improve sensitivity to gravitational waves.
    b. Quantum sensors take advantage of the fact that physical qubits are extremely sensitive to their surroundings. The same fragility that leads to rapid decoherence enables precise sensors. Examples include magnetometers, single-photon detectors, and atomic clocks for improvements in medical imaging and navigation, position, and timing.
    c. Quantum sensing has vastly improved the precision and accuracy of measurements of fundamental constants, freeing the International System of Units from its dependence on one-of-a-kind artifacts. Measurement units are now defined through these fundamental constants, like the speed of light and Planck's constant.