QIS K-12 Key Concepts for CS Classes

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Preamble:

This document, QIS K-12 Key Concepts for CS Classes, is a companion to the QIS K-12 Key Concepts. The latter document is written for QIS overall, trying to encompass the perspectives of many fields, including physics, computer science, mathematics, and chemistry. The purpose of this document is to introduce and express computational concepts within QIS in a way that is accessible, engaging, and relevant to today's computer science learners and their teachers. This document can be the starting point for a framework, learning trajectories, and activities for computer science courses.

From a high level, there are a few differences between this document and the QIS K-12 Key Concepts:

1. Concepts have been added (Quantum Operations), reordered (Qubits), and removed (Quantum Sensing).
2. Some concepts have been reworded to use language and provide background information that is accessible to middle-school and high-school CS students.
3. Some supporting fundamentals (sub-concepts) have been added, removed, and reworded.

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. **(QIS)**

Quantum information science combines information theory and computer science, following the laws of quantum mechanics, to process information in fundamentally new ways. **(QIS.A)**

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. **(QIS.B)**

Quantum sensing takes advantage of the fact that quantum systems are extremely sensitive to their surroundings to detect and measure physical properties with the highest precision allowed by quantum mechanics. **(QIS.C)**

QIS

The **quantum bit**, or **qubit**, is the fundamental unit of quantum information. **(Qubit)**

Unlike a classical bit, each qubit can represent not only a single 0 or 1, but hold both in **superposition**, with a probability of a measurement outcome of 0 or 1. The probabilities must add to 100%. **(Qubit.A)**

Beyond holding 0 or 1, a qubit also has a phase, which can also be held in superposition and measured. **(Qubit.B)**

A set of n classical bits can hold only one of 2^n possible states, but a set of n qubits can hold a superposition of any combination of these states. **(Qubit.C)**

Qubits can be implemented with a variety of technologies like polarization states of light, energy states of an atom, or spin states of an electron. **(Qubit.D)**

Qubits are fragile; environmental disturbances and measurement almost always affect the computation. **(Qubit.E)**

Qubits

A **quantum state** is a mathematical representation of the complete state of a quantum system consisting of one or more qubits. **(State)**

The state of a single qubit must describe the probability of each possible measurement outcome for its bit value (0 vs 1) and phase. **(State.A)**

The state of a single qubit can be represented as a point on a unit sphere (called the Bloch sphere), with the position indicating the probability of measuring phase and 0 vs 1. **(State.B)**

The state of a single qubit can be represented by two complex numbers (called bra-ket notation), from which you can calculate the phase and probability of measuring 0 or 1. **(State.C)**

The state of an n-qubit system can be represented by 2^n complex numbers, organized in a 1-d array (implementing vector notation), from which you can calculate the probability of measuring any combination of measurement outcomes. **(State.D)**

State

Measurement

In order to obtain information from a qubit, a **measurement** is performed. **(Measure)**

A single measurement does not reveal the complete state (the probability of measuring each outcome) - it only returns a single value. **(Measure.A)**

Performing a measurement causes a change to the qubit state, collapsing the complex state into the single measured outcome. Subsequent measurements without additional operations will yield the same result. **(Measure.B)**

Repeated measurements on identically prepared quantum systems are required to determine the full quantum state. **(Measure.C)**

Quantum states cannot be copied or duplicated. **(Measure.D)**

Quantum applications are designed to carefully manipulate fragile quantum systems without intermediate measurements to increase the probability that the final measurement will produce the intended result. **(Measure.E)**

Quantum Operations

Quantum operations, or quantum gates, are used to modify quantum state. **(Ops)**

Quantum operations affect a qubit's state, changing the probability of measuring 0 or 1, its phase, or both. **(Ops.A)**

Some quantum operations act on a single qubit, whereas others act on two or more qubits. **(Ops.B)**

Each quantum operation is expressed mathematically as a 2-d array (matrix) . Given a 1-d array (vector) that describes the starting quantum state of one or more qubits, the resulting state can be calculated using matrix multiplication. **(Ops.C)**

All quantum operations must be reversible. **(Ops.D)**

Quantum operations are implemented without performing a measurement. **(Ops.E)**

Entanglement

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

When multiple qubits in superposition are entangled, the measurement outcome of one affects the state of the other(s). **(Entangle.A)**

An entangled quantum system of two or more qubits cannot be described solely by expressing the individual quantum states of each qubit. **(Entangle.B)**

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

Undesired interaction with the surrounding environment causes **decoherence,** which erodes superposition and entanglement. Decoherence can be caused by light, vibration, heat, or magnetic fields. **(Decoherence.A)**

The amount and type of shielding to prevent decoherence depends on the qubit technology being used. **(Decoherence.B)**

High decoherence rates limit the number of qubits and quantum operations that can be accurately performed. **(Decoherence.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. **(Decoherence.D)**

Decoherence

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

Entanglement, superposition, and phase are key properties of quantum systems that provide quantum computing its computational advantage over classical computing. **(QCs.A)**

There are several quantum application areas that quantum computers may accelerate: breaking current cryptography protocols, molecular simulations, and optimizations. **(QCs.B)**

Qubits can represent information compactly; more information can be stored and processed using 100 qubits than with the largest conceivable classical supercomputer. **(QCs.C)**

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 through all possible solutions to a problem (quadratic speed-up). However, there is no speed advantage for many other types of computations. **(QCs.D)**

QCs

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

Quantum teleportation is a protocol that uses entanglement to destroy quantum information at one location and recreate it at a second site more reliably and faster than physically transferring the qubits themselves. **(Communication.A)**

Quantum cryptography uses the fragility of quantum systems to detect an eavesdropper's interloping measurement. **(Communication.B)**

Communication