QIS KEY CONCEPTS for MIDDLE SCHOOL

Q12EDUCATION.ORG

QIS KEY CONCEPTS FOR MIDDLE SCHOOL

FRAMEWORK FOR K-12 QUANTUM EDUCATION

The world is in the midst of a second quantum revolution due to our ability to exquisitely control quantum systems and harness them for applications in quantum computing, communications, and sensing. Quantum information science (QIS) is an area of STEM that makes use of the laws of quantum physics for the storage, transmission, manipulation, processing, or measurement of information.

After the passage of the US National Quantum Initiative Act in December 2018 [1], the National Science Foundation and the White House Office of Science and Technology Policy (WHOSTP) assembled an interagency working group and subsequently facilitated a workshop titled “Key Concepts for Future Quantum Information Science Learners” that focused on identifying core concepts essential for helping pre-college students engage with QIS. The output of this workshop was intended as a starting point for future curricular and educator activities [2-4] aimed at K-12 and beyond. Helping pre-college students learn the QIS Key Concepts could effectively introduce them to the Second Quantum Revolution and inspire them to become future contributors and leaders in the growing field of QIS spanning quantum computing, communication, and sensing. The framework for K-12 quantum education outlined here is an expansion of the original QIS Key Concepts, providing a detailed route towards including QIS topics in K-12 physics, chemistry, computer science and mathematics classes. The framework will be released in sections as it is completed for each subject.

As QIS is an emerging area of science connecting multiple disciplines, content and curricula developed to teach QIS should follow the best practices. The K-12 quantum education framework is intended to provide some scaffolding for creating future curricula and approaches to integrating QIS into physics, computer science, mathematics, and chemistry (mathematics and chemistry are not yet complete). The framework is expected to evolve over time, with input from educators and educational researchers.

WHY QUANTUM EDUCATION AT THE K-12 LEVEL?

Starting quantum education in K-12 provides a larger, more diverse pool of students the opportunity to learn about this exciting field so that they can become the future leaders in this rapidly growing field. This is especially important because over the past century during which the first quantum revolution unfolded, the quantum-related fields have lacked gender, racial, and ethnic diversity. We must tap into the talents of students from diverse demographic groups in order to maintain our leadership in science and technology. Early introduction to quantum science can include information on applications and societal relevance, which will hopefully spark excitement and lead more students into later coursework and careers in STEM. Also, starting early with a conceptual, intuitive approach that doesn't rely on advanced mathematics will likely increase quantum awareness with more students, even those who do not pursue a career in QIS. In the long term, this will potentially improve public perception of QIS, moving it out of the weird, spooky, incomprehensible, unfamiliar realm.

WHAT ARE SOME CONSIDERATIONS TO TAKE INTO ACCOUNT WHEN INTRODUCING QIS INTO THE K-12 CLASSROOM?

As an emerging field that has traditionally been the realm of advanced undergraduate and graduate study with an aura of complexity, educators designing and delivering curriculum should keep the following in mind when integrating QIS into their classrooms.

1. Because existing materials in QIS are designed for more advanced students, the materials need to be adjusted to be age-appropriate for and build on prior knowledge of target students. As new educational research and data on implementation come in, the materials will change and improve over time.
2. Because the area may be intimidating, and there is no expectation in college that students have already learned this, motivational goals such as higher self-efficacy and a sense of belonging and identity [5-11] should be on equal footing with technical goals. Therefore, classrooms should focus on the following considerations:
    - Maintain a supportive atmosphere that encourages questions and exploration
    - Offer collaborative, exploratory activities
    - Offer a low-stakes educational setting (e.g. little time pressure without aggressive testing)
    - When relevant to the STEM subject, employ a learning cycle approach to develop models of quantum systems and phenomena, plan and carry out investigations to test their models, analyze and interpret data, obtain, evaluate, and communicate their findings

QIS K-12 KEY CONCEPTS MIDDLE-SCHOOL FOCUS GROUP

Quantum information science leverages quantum mechanics to develop new capabilities in computing, sensing, and communications. In middle-school classrooms, there are many natural points of integration, such as probability, atomic structure, the nature of light, and computational thinking. The purpose of the QIS K-12 Key Concepts Middle-School Focus Group was to create an initial set of expectations and learning goals, which will be useful to curriculum developers and teachers seeking to develop lessons and activities for teaching QIS K12 Key Concepts.

The focus group brought together a range of experts, including educators familiar with both teaching and research of related concepts at various levels. The members were:

April Campbell, Jennings Middle School, Seffner, FL

* John Donohue, Waterloo Institute for Quantum Computing, Ontario

* Emily Edwards, University of Illinois Urbana-Champaign, Urbana, IL

* Diana Franklin, University of Chicago, Chicago, IL

Isabella Huang, Summit Middle School, Boulder, CO

George Hunkele, Harborside Middle School, Milford, CT

Tunde Kushimo, Texas Tech University, Lubbock, TX

Shardae Monroe, Sulphur Springs PK-8 Community Partnership School, Tampa, FL

Gwendolyn Morris, Matawan Aberdeen Middle School, Cliffwood, NJ

Beverly Owens, Cleveland Early College High School, Shelby, NC

Sharlyn Robin, Stephen Decatur Middle School, Clinton, MD

Jeremy Schwartz, University of Chicago Laboratory School, Chicago, IL

* Chandralekha Singh, University of Pittsburgh, Pittsburgh, PA

Jennifer Smith, Illinois Virtual Schools and Academy, Mahomet, IL

Anne Tabor-Morris, Georgian Court University, Lakewood, NJ

Delonjie Tyson, Hillsborough County , Tampa, FL

Andrea Vode, University of Chicago Laboratory Schools, Chicago, IL

Laura Von Staden, Williams Middle Magnet, Tampa, FL

* Brent Yen, University of Chicago, Chicago, IL

Liang Zeng, The University of Texas Rio Grande Valley, Edinburg, TX

* *Designates working group leads, conveners, and/or framework editors.*

The output from this group was a series of expectations and outcomes for each QIS Key Concept. This initial framework is intended to evolve over time as quantum education for K-12 develops.

1. QUANTUM INFORMATION SCIENCE

KEY CONCEPT

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.

NOTE

The definition of QIS could be discussed as a precursor to any of the other concepts, or in discussions of career opportunities in the field.

MS 1.1 QUANTUM INFORMATION SCIENCE

DESCRIPTION

Potential careers related to quantum information science include, but are not limited to:

- Experimental research scientists (physics and chemistry)
- Theoretical physicists and mathematicians
- Algorithm designers and computational complexity experts
- Application programmers
- Quantum computer system architects
- Cryptographers and information security experts
- Software developer and engineers
- Cryogenics and vacuum technologists
- Fabrication and nanotechnology engineers
- Medical imaging technologists and researchers
- Business development experts
- Science communicators

LEARNING OUTCOMES

Middle School Learning Outcome(s)

Students will be able to describe many career opportunities available for skilled workers with expertise in science, technology, engineering, and mathematics (STEM) fields.

QIS Learning Outcome(s)

Students will be able to describe many careers available in the newly developing quantum workforce, which requires people with diverse skill sets working in a multidisciplinary field.

(MS.1.1)

NOTE

The definition of QIS could be discussed as a precursor to any of the other concepts, or in discussions of career opportunities in the field.

2. QUANTUM STATE

KEY CONCEPT

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.

MS Science 2.1 QUANTUM STATE

DESCRIPTION

The state of a classical object (for example, a ball) is defined by its properties, such as mass, position, velocity, and potentially many others.

The state of a quantum object (for example, an atom) is defined by its properties as well. However, these properties may not be well-defined for certain states.

In quantum mechanics, it is possible for the object to be in a superposition of two states, meaning it is uncertain which one it will be found in when it is measured.

For example, the state of a classical coin is either heads or tails. In quantum mechanics, the state of the quantum coin may be a superposition of heads and tails, meaning the outcome of the coin flip is undetermined until it is measured.

The quantum state is an important concept that helps us predict the probabilities of measuring different outcomes in experiments, and must be engineered carefully when building quantum bits (qubits) for different quantum technologies.

LEARNING OUTCOMES

Science Learning Outcome(s)

- Students will be able to explain that the state of a system defines its properties and can be used to make predictions about its behavior, including the outcomes of measurements and experiments.

QIS Learning Outcome(s)

- Students will be able to explain that quantum states may have indefinite (probabilistic) outcomes, meaning that the outcomes are not determined until they are measured, if they are in a superposition of different possibilities.

(MS.Sci.2.1)

POSSIBLE ACTIVITIES

- Students will build a model of a classical process with uncertain outcomes until a measurement is made (e.g., the result of a coin flip) and compare and contrast with quantum equivalents.

3. QUANTUM MEASUREMENT

KEY CONCEPT

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. *(See section on qubits)*

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.

MS Science 3.1 — QUANTUM MEASUREMENT

DESCRIPTION

The outcomes of certain classical events may be difficult to know in advance, such as the result of a coin flip. By performing the task many times, we can estimate the probability of each event occurring.

The outcomes of measurements on quantum systems are fundamentally uncertain (probabilistic) and cannot be known in advance of a measurement. Performing the experiment many times can still help us infer the underlying probability distribution.

LEARNING OUTCOMES

Science Learning Outcome(s)

- Students will explain that the outcomes of experiments may follow a probability distribution.
- Students will demonstrate that more data can be gathered to discover the underlying probability distribution with greater precision and build more accurate models.

QIS Learning Outcome(s)

- Students will be able to explain that quantum measurements always follow probability distributions and that many measurements are needed to infer the quantum state.

(MS.Sci.3.1)

POSSIBLE ACTIVITIES

1. Measuring the probability distribution of a coin or die (biased vs. unbiased).

STANDARDS ALIGNMENT

NGSS:

- MS-ETS1-3 - Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

MS Science 3.2 QUANTUM MEASUREMENT

DESCRIPTION

When you measure a property of a system (such as its temperature), we must be careful not to change the system with the device we use to measure it.

In quantum mechanics, we inevitably introduce changes to the state of the system when we make a measurement.

LEARNING OUTCOMES

Science Learning Outcome(s)

- Students will demonstrate how measuring a property of a system can change the state of the system.

QIS Learning Outcome(s)

- Students will be able to explain that quantum measurements unavoidably change the state of the system.

(MS.Sci.3.2)

POSSIBLE ACTIVITIES

1. Students will brainstorm ways that traditional measurements can affect the state of a system (for example, if you measure the temperature of a glass of water with your hand, you will warm up the glass of water by touching it).

2. Students will show that measuring the polarization in between two crossed polarizers with a third polarizer increases the amount of light through the system, which can be described as a change of polarization state due to measurement.

MS Mathematics 3.1 — QUANTUM MEASUREMENT

DESCRIPTION

The outcomes of quantum measurements are inherently uncertain (probabilistic). To describe the possible outcomes of a quantum measurement, we use probability distributions. Each possible outcome of the measurement has a particular probability that expresses the likelihood of that event occurring.

Measurement outcomes that are less likely will have probabilities that are smaller than the outcomes that are more likely.

The sum of the probabilities for all of the possible measurement outcomes equals 1. This expresses the fact that at least one of the outcomes must occur.

LEARNING OUTCOMES

Math Learning Outcome(s)

- Students will understand the basic definitions and rules of probability.
- Students will compute the probability of simple events and compound events.

QIS Learning Outcome(s)

- Students will be able to explain that quantum measurements always follow probability distributions.

(MS.Math.3.1)

POSSIBLE ACTIVITIES

1. Students will brainstorm ways that traditional measurements can affect the state of a system (for example, if you measure the temperature of a glass of water with your hand, you will warm up the glass of water by touching it).
2. Students will show that measuring the polarization in between two crossed polarizers with a third polarizer increases the amount of light through the system, which can be described as a change of polarization state due to measurement.

STANDARDS ALIGNMENT

Common Core State Standard(s):

- 7.SP.5 - Understand that the probability of a chance event is a number between and 1 that expresses the likelihood of the event occurring. Larger numbers indicate greater likelihood. A probability near 0 indicates an unlikely event, a probability around 1/2 indicates an event that is neither unlikely nor likely, and a probability near 1 indicates a likely event.

MS Mathematics 3.2 QUANTUM MEASUREMENT

DESCRIPTION

For any process which has a probability associated with it, multiple data points are required to estimate the probability.

Quantum states determine the probabilities of the outcomes of quantum measurements. We can perform quantum measurements to learn more information about the quantum state.

LEARNING OUTCOMES

Math Learning Outcome(s)

- Students will estimate the probability of a probabilistic event by collecting data on the process produced by it.

QIS Learning Outcome(s)

- Students will be able to explain that a single measurement is not sufficient to determine a quantum state. Many measurements are needed to learn the quantum state.

(MS.Math.3.2)

POSSIBLE ACTIVITIES

1. Students can engage in experimental probability activities, such as “experiments” in which they flip a coin over and over. Students see how it matches up to the theoretical probability.
    - If you flip 100 pennies, how many will come up heads vs. tails? Theoretically, and then when you actually do it (experimental)?
2. Start with spinners, dice, and coins. If you spin the spinner, roll the die, then flip the coin, what is the probability you will get a certain combination?

STANDARDS ALIGNMENT

Common Core State Standards:

- 7.SP.6 - Approximate the probability of a chance event by collecting data on the chance process that produces it and observing its long-run relative frequency, and predict the approximate relative frequency given the probability. For example, when rolling a number cube 600 times, predict that a 3 or 6 would be rolled roughly 200 times, but probably not exactly 200 times.

MS Computer Science 3.1 QUANTUM MEASUREMENT

DESCRIPTION

Computational models, such as AI and language models, follow probability distributions. Creating these models required many observations to test and develop these models' "beliefs."

Quantum measurements are required to learn the state of a quantum system.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will explain how many types of computational models follow probability distributions.
- Students will understand that to develop the model's "beliefs" one must measure the outcomes and test multiple times.

QIS Learning Outcome(s)

- Students will be able to explain that quantum measurements always follow probability distributions and that many measurements are needed to learn the quantum state.

(MS.CS.3.1)

STANDARDS ALIGNMENT

CSTA:

- 2-DA-09 - Refine computational models based on the data they have generated.
- 3B-DA-07 - Evaluate the ability of models and simulations to test and support the refinement of hypotheses.

4. QUBITS

KEY CONCEPT

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. *(See section on quantum computing)*

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

MS Science 4.1

QUBITS

DESCRIPTION

Classical information is stored as collections of binary digits (bits).

- Each bit can take the value 0 or 1.

To build devices in real life, those bits must be encoded into something physical.

- A coin being heads (0) or tails (1) can be used to encode a bit of information.
- Whether the voltage across a capacitor is high or low (above or below some threshold) tells us whether each bit in a computer is a 0 or 1.

Quantum bits (qubits) are encoded in quantum systems.

- Qubits can be 0, 1, or a superposition of 0 and 1.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will describe how, in information technology, information must be stored in a collection of physical systems, each with two possible states.

QIS Learning Outcome(s)

- Students will describe how systems which obey the laws of quantum mechanics can store information as quantum bits.

(MS.Science.4.1)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS Science 4.2

QUBITS

DESCRIPTION

In order to encode a bit of information, there must be two distinguishable states, one of which corresponds to "0" and the other to "1".

Electrons in atoms can only have specific energies, and transitions between them correspond to the colors of their emission spectrum. We can identify two of these energy levels and label them as "0" and "1".

By using lasers and magnetic fields to control the energy of the electrons, we can put them into the "0" state, the "1" state, or a superposition of "0" and "1".

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to explain that matter is made up of smaller particles like atoms and electrons.

QIS Learning Outcome(s)

- Students will be able to explain that atoms have energy levels and information can be stored/ encoded in them.

(MS.Science.4.2)

POSSIBLE ACTIVITIES

1. Students will identify elements and light sources by their emission/absorption spectrum and compare them with scientific databases.

STANDARDS ALIGNMENT

NGSS:

- MS-PS1-1 - Develop models to describe the atomic composition of simple molecules and extended structures.
- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS Science 4.3
QUBITS

DESCRIPTION

Light carries energy as electromagnetic radiation.

- Light has various properties, like color, direction, and polarization.

Information can be encoded using various properties of light.

- Light signals are sent in optical fiber to deliver high-speed internet.
- Light can have one of two polarization states, which allows us to encode bits into photons and beams of light.

At the quantum level, light is made up of indivisible units called photons.

- Qubits can be encoded in many of the same properties for single photons, such as a superposition of polarization states.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will demonstrate that light carries energy as electromagnetic radiation.

QIS Learning Outcome(s)

- Students will be able to explain that light consists of discrete units of energy called photons.
- Students will demonstrate that classical and quantum information can be encoded into the various properties of light, such as its polarization.

(MS.Science.4.3)

POSSIBLE ACTIVITIES

1. Students can develop a communication system that uses the polarization of light to encode 0's and 1's, which can be measured with polarizers or sunglasses.
2. Students can demonstrate how polarization is manipulated and controlled using birefringent materials such as clear tape.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-1 - Use mathematical representations to describe a simple model for waves that includes how the amplitude of a wave is related to the energy in a wave.
- MS-PS4-2 - Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.
- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS Science 4.4

QUBITS

DESCRIPTION

Electrical current flows through conductive elements like wires, and is stopped by insulating elements like plastic.

At low temperatures, certain materials become superconductors, meaning they have no electrical resistance whatsoever and current can flow freely.

Superconductors can be used to build both high-power electromagnets and qubits encoded in the properties of current in microscopic circuits.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will explain the behavior of electric current and identify various circuit components.

QIS Learning Outcome(s)

- Students will be able to explain the basic idea of superconductors and their applications, including as qubits.

(MS.Science.4.4)

POSSIBLE ACTIVITIES

1. Students can develop a communication system that uses the polarization of light to encode 0's and 1's, which can be measured with polarizers or sunglasses.
2. Students can demonstrate how polarization is manipulated and controlled using birefringent materials such as clear tape.

STANDARDS ALIGNMENT

NGSS:

- MS-PS2-3 - Ask questions about data to determine the factors that affect the strength of electric and magnetic forces.
- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS Mathematics 4.1

QUBITS

DESCRIPTION

Qubits store information in the form of quantum states. A quantum state expresses the probabilities of every possible measurement outcome.

The concept of probability is introduced in 7th grade, when students learn how to interpret probabilities between 0 and 1.

The idea of superposition of quantum states provides an application where students can explore the concept of probability.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will understand that the probability of an event is a number between 0 and 1 that expresses the likelihood that the event will occur.

QIS Learning Outcome(s)

- A qubit holds information in superposition, with a certain probability of each outcome occurring when the qubit is measured.

(MS.Math.4.1)

POSSIBLE ACTIVITIES

1. Students can develop a communication system that uses the polarization of light to encode 0's and 1's, which can be measured with polarizers or sunglasses.
2. Students can demonstrate how polarization is manipulated and controlled using birefringent materials such as clear tape.

STANDARDS ALIGNMENT

Common Core State Standard(s):

- 7.SP.5 - Understand that the probability of a chance event is a number between 0 and 1 that expresses the likelihood of the event occurring. Larger numbers indicate greater likelihood. A probability near 0 indicates an unlikely event, a probability around 1/2 indicates an event that is neither unlikely nor likely, and a probability near 1 indicates a likely event.

MS Computer Science 4.1

QUBITS

DESCRIPTION

Classical computers store data in the form of binary digits (bits) which are sequences of 0s and 1s.

For example, every letter or image or sound is translated from a form that people can understand into a sequence of bits (0s and 1s) which is a form of data that computers are able to store and process.

A single bit can exist in one of two values, 0 or 1. Two bits can exist in one of four possible values (00, 01, 10, or 11). More generally, a set of n classical bits can exist in one of 2^n possible states.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will explain how data can be encoded using multiple encoding schemes on a computer.

QIS Learning Outcome(s)

- At a particular moment in time, a set of n classical bits can exist in only one of 2^n possible states.

(MS.CS.4.1)

POSSIBLE ACTIVITIES

1. Each rgb (Red-Green-Blue) value for a pixel is limited to the values 0-255 because 8 bits are used to store them, and any set of n classical bits can exist in only one of 2^n possible states.

STANDARDS ALIGNMENT

CSTA:

- 2-DA-07 - Represent data using multiple encoding schemes.
- 3A-CS-02 - Compare levels of abstraction and interactions between application software, system software, and hardware layers.

MS Computer Science 4.2

QUBITS

DESCRIPTION

A set of n qubits can exist in a superposition of 2^n possible states.

For example, one qubit can exist in a superposition of two possible states (0 and 1). Two qubits can exist in a superposition of four possible states (00, 01, 10, and 11).

The ability of quantum bits to store more information than classical bits allows quantum computers to solve certain computational problems faster than classical computers. Examples include:

- Simulation of quantum systems, such as atoms and molecules.
- Finding solutions to problems in areas like cryptography.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will explain how data can be encoded using multiple encoding schemes on a computer.

QIS Learning Outcome(s)

- Students will explain how quantum bits store more information than classical bits.

(MS.CS.4.2)

POSSIBLE ACTIVITIES

1. Each rgb (Red-Green-Blue) value for a pixel is limited to the values 0-255 because 8 bits are used to store them, and any set of n classical bits can exist in only one of 2^n possible states.

STANDARDS ALIGNMENT

CSTA:

- 2-DA-07 - Represent data using multiple encoding schemes.
- 3A-CS-02 - Compare levels of abstraction and interactions between application software, system software, and hardware layers.

5. ENTANGLEMENT

KEY CONCEPT

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.

MS Science 5.1
ENTANGLEMENT

DESCRIPTION

Entanglement describes a relationship between two or more quantum systems that can occur when they interact with each other.

Because of conservation of energy, if one system loses a certain amount of energy, it must be gained by another system.

- The energy of each individual system may change, but the total energy is the same.

As a specific example, two qubits may be connected such that energy lost by one is gained by the other. If the first qubit is in a superposition of losing energy or not, the second qubit's energy will be dependent on the first.

- These two systems are entangled with each other; the properties of the second qubit cannot be described without considering the first qubit.
- The individual energy of each qubit is uncertain before they are measured, but the energy of the first qubit is correlated to the energy of the second qubit because the total energy is fixed.
- After measuring the first qubit, the energy of the second qubit is certain.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to explain conservation laws, such as conservation of energy.

QIS Learning Outcome(s)

- Students will identify how conservation laws at the quantum level result in correlations between particles, which is called entanglement.

(MS.Sci.5.1)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

NGSS:

- MS-PS3-4 - Plan an investigation to determine the relationships among the energy transferred, the type of matter, the mass, and the change in the average kinetic energy of the particles as measured by the temperature of the sample.

MS Mathematics 5.1

ENTANGLEMENT

DESCRIPTION

To compute the probability of two independent events, we compute the product of the probabilities of each individual event.

Two qubits can be independent or entangled with each other. When qubits are independent, the probability of measurement outcomes are computed by multiplying the probabilities of the outcomes for each individual qubit.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to calculate the probability of two independent events occurring by computing the product of the probabilities of each event occurring.

QIS Learning Outcome(s)

- Students will describe how when multiple qubits in superposition are not entangled, their measurement outcomes are independent.
- Students will calculate the probability of a measurement outcome for multiple independent qubits that are not entangled by computing the product of the probabilities of the corresponding measurement outcomes of each qubit.

(MS.Math.5.1)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

Common Core State Standard(s):

- HS.S.CP.2 - Understand that two events A and B are independent if the probability of A and B occurring together is the product of their probabilities, and use this characterization to determine if they are independent.

MS Mathematics 5.2

ENTANGLEMENT

DESCRIPTION

When two or more qubits are entangled with each other, their measurement outcomes will become correlated.

- For example, if we make measurements on two qubits in a certain entangled state, their measurement outcomes will always be the same, either both 0 or both 1.
- It is also possible for the measurement outcomes for two entangled qubits to always be the opposite of each other, where one outcome is 0 while the other outcome is 1.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will identify a dependent event as one in which the outcome is based on information from another event.
- Students will understand that if the probability of two events occurring is different than the product of their individual probabilities, then the outcomes of those events are correlated or dependent.

QIS Learning Outcome(s)

- Students will understand that when multiple qubits in superposition are entangled, their measurement outcomes are correlated.
- Students will identify an entangled system of multiple qubits as one which cannot be described solely by specifying an individual quantum state for each qubit.

(MS.Math.5.2)

MS Mathematics 5.3

ENTANGLEMENT

DESCRIPTION

Entanglement is a mathematical correlation between measurement outcomes. The measurement of one can cause a change in another. Predicate logic expresses relationships between events. While these relationships are not identical, in both cases, they are describing dependencies.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will understand that there are many mathematical relationships that can exist between events and that predicate logic (syllogisms) is one way of expressing some types of relationships.
- Syllogisms - predicate logic (proof geometry)

QIS Learning Outcome(s)

- Students will understand that entanglement is an inseparable relationship between multiple qubits.

(MS.Math.5.3)

POSSIBLE ACTIVITIES

1. Students can first complete a number of syllogisms with predicate logic. The instructor can then introduce another relationship - *entanglement* - and discuss the fact that it causes a dependent relationship between two entities. They can then look at some syllogisms that might relate, such as whether it has transitive property (if *a* is entangled with *b*, *b* is entangled with *c*, is a entangled with *c*?)

MS Computer Science 5.1

ENTANGLEMENT

DESCRIPTION

Entanglement is a mathematical correlation between measurement outcomes. The measurement of one can cause a change in another.

Conditionals are not the same as entanglement, but it is a form of dependence, in which the value of one variable can be used to affect the value of another variable.

The CS learning outcomes highlight several aspects of dependence - identifying their existence, implementation with if/then/else statements, and identifying whether or not a specific scenario requires conditional statements.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to identify different kinds of dependencies in computing systems. Control dependencies, or performing an action depending on something else in the system, can be implemented using if/then/else statements.

- Students will implement if/then/else statements, including nested ones, by thinking through whether the second action is dependent on or independent of the first if statement.

QIS Learning Outcome(s)

- Students will understand that entanglement is an inseparable relationship between multiple qubits.

(MS.CS.5.1)

6. COHERENCE/DECOHERENCE

KEY CONCEPT

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.

MS Science 6.1 DECOHERENCE

DESCRIPTION

External influences affect many systems

- Radiation can cause mutations in DNA
- Contamination can degrade chemical samples
- Contact with air and bacteria can change or spoil food, such as an avocado turning brown when left out

External influences can also affect qubits and other quantum systems

- Light from unintended sources may interact with an atomic qubit, changing it from the intended quantum state
- A qubit encoded in a photon may be absorbed by an air molecule, losing the information stored within it

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will explain how outside influences can disturb an experiment and change the results.

QIS Learning Outcome(s)

- Students will be able to explain how qubits degrade in quality when they interact with the surrounding environment through a process called decoherence.

(MS.Sci.6.1)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

NGSS:

- MS-ETS1-1 - Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

MS Science 6.2 DECOHERENCE

DESCRIPTION

Systems used in science and technology decay after a certain time

- Example: Carbon dating is based on the natural decay of a carbon from one isotope to another

The information stored in qubits also has a lifetime during which operations must be completed.

- An atom in an excited state will naturally relax to the ground state after a certain period of time, even if isolated from other sources of decoherence.
- External sources of decoherence, such as radiation, can reduce the useful coherence time of a qubit even further.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will learn how certain systems have a natural time scale on which they are stable.

QIS Learning Outcome(s)

- Qubits often have a natural lifetime or coherence time after which their quantum state is unstable.
- All computations and qubit operations must take place in a time shorter than the coherence time of the qubits.

(MS.Sci.6.2)

POSSIBLE ACTIVITIES

1. Students can perform a radiometric dating lab using coins or another two-sided object to model a probabilistic process with a predictable time scale.

STANDARDS ALIGNMENT

NGSS:

- MS-ETS1-1 - Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.

MS Science 6.3 DECOHERENCE

DESCRIPTION

Both natural and man-made structures have systems in place to correct for errors and contamination.

- DNA has repetitive sections included in its structure so that it can withstand modest errors without losing its function.
- Critical devices in your life have a sensor to flag when a failure/error is occurring (e.g., a phone detecting when the charging cord is wet, a smoke detector beeping when the battery is empty).

Qubits should be designed with these considerations in mind as well.

- Quantum error correction uses redundancy and other techniques to protect the information encoded in a qubit.
- Qubits are often kept in high-vacuum and at very low temperatures to reduce the effects of decoherence.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will demonstrate how systems can be engineered to be resilient against disturbances, errors and malfunctions.

QIS Learning Outcome(s)

- Students will be able to explain how qubits can be engineered to be resilient against decoherence.

(MS.Sci.6.3)

STANDARDS ALIGNMENT

NGSS:

- MS-ETS1-1 - Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-3 - Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.
- MS-ETS1-4 - Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

MS Computer Science 6.1

DECOHERENCE

DESCRIPTION

When computers store, process, or communicate information with other computing devices, errors can occur due to interactions with their external environment.

- Radiation or vibrations can affect computing devices.
- Computer errors are more common when there is a violent storm.

Quantum computers store and process fragile quantum states, which can quickly degrade and lose information due to interactions with their external environment.

Qubits degrade and lose information much more quickly compared to bits in a classical computer.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will demonstrate how systems can be engineered to be resilient against disturbances, errors and malfunctions.

QIS Learning Outcome(s)

- Students will be able to explain how qubits can be engineered to be resilient against decoherence.

(MS.CS.6.1)

MS Computer Science 6.2

DECOHERENCE

DESCRIPTION

Computers that are attempting to communicate with another computing device need to detect errors that occur during transmission.

Computer systems use different methods to detect and correct errors.

- A message can be resent if an error occurred.
- Computers can communicate extra information that serves as a checksum to verify whether or not the transmission has an error (detection).

Quantum computers require extensive error detection and correction procedures, because errors happen much more often than in classical computers.

- Quantum error correction uses redundancy and other techniques to protect the information encoded in a qubit.
- Qubits are often kept in high-vacuum and at very low temperatures to reduce the effects of decoherence.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will describe different methods that computer systems use to detect and correct errors that occur due to interactions with their external environment.

QIS Learning Outcome(s)

- Students will identify methods that are used to correct and protect against errors in quantum computers.

(MS.CS.6.2)

STANDARDS ALIGNMENT

CSTA:

- 2-NI-04 - Model the role of protocols in transmitting data across networks and the Internet. *Protocols are rules that define how messages between computers are sent. They determine how quickly and securely information is transmitted across networks and the Internet, as well as how to handle errors in transmission.*

MS Computer Science 6.3

DECOHERENCE

DESCRIPTION

Computer programmers and engineers need to perform tests to locate and identify errors when programs do not operate as they are designed.

Quantum computers are a new type of computing technology. Quantum programs currently are created from quantum operations that are relatively unreliable compared to operations in a classical computer.

Programmers and engineers who are designing quantum computers need to identify and fix the type of errors that occur when operating a quantum computer.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to perform tests to identify when their code has errors, use debugging tools to find the source of the bug, and brainstorm solutions to fix the bug.

QIS Learning Outcome(s)

- Students will be able to identify an error in a simple quantum program, such as when a quantum operation gives an incorrect result.
- Students will brainstorm possible sources of error in a quantum computer.

(MS.CS.6.3)

STANDARDS ALIGNMENT

CSTA:

- 1A-AP-14 - Debug (identify and fix) errors in an algorithm or program that includes sequences and simple loops.
- 1B-AP-15 - Test and debug (identify and fix errors) a program or algorithm to ensure it runs as intended.
- 2-AP-17 - Systematically test and refine programs using a range of test cases.

MS Computer Science 6.4

DECOHERENCE

DESCRIPTION

Computer engineering problems often have several design constraints and specifications.

Solutions to computer engineering problems must adhere to these design constraints.

Designing and programming quantum computers have design constraints.

- Decoherence limits the number and quality of qubits that can be created in a quantum computer.
- Creating and maintaining the quantum properties of the qubits, such as entanglement or superposition, are design constraints for building a quantum computer.
- Writing programs for a quantum computer depend on the design constraints on the computing power of the quantum computer.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will describe how computer engineering problems have specifications and design constraints.

QIS Learning Outcome(s)

- Students will describe how designing and programming useful quantum computers have design constraints related to decoherence and the number and quality of qubits currently available in quantum computers.

(MS.CS.6.4)

STANDARDS ALIGNMENT

CSTA:

- 3B-AP-21 - Develop and use a series of test cases to verify that a program performs according to its design specifications

7. QUANTUM COMPUTING

KEY CONCEPT

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.

MS Science 7.1 QUANTUM COMPUTING

DESCRIPTION

Computers of today are used to solve problems that have changed our lives in many ways, but there are some problems that are too difficult for even the most powerful supercomputers.

Quantum computers of the future can be used to solve some problems much more efficiently than traditional computers.

- Quantum computers are able to factor large numbers very efficiently, with applications in cryptography and internet security.
- Quantum computers can be used to simulate the physics and chemistry of the world around us, with potential applications in drug design, medical technology, materials science, fertilizer development, and more.

Quantum computers are special-purpose devices that will work alongside traditional methods of computing.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to describe how the development of computers in the 1900s enabled the development of many modern technologies.

QIS Learning Outcome(s)

- Students will identify how future societal advancements will arise from the development of new technologies like quantum computing.

(MS.Sci.7.1; same as MS.CS.7.1)

POSSIBLE ACTIVITIES

1. Students will reflect on ways in which computing has changed society or how different computing devices are used for different purposes (for example, comparing and contrasting phones, laptops, calculators, and supercomputers).

STANDARDS ALIGNMENT

NGSS:

- MS-PS1-3 - Gather and make sense of information to describe that synthetic materials come from natural resources and impact society.
- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-3 - Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

MS Science 7.2 QUANTUM COMPUTING

DESCRIPTION

Traditional computers process information stored in classical bits, which can take the value of “0” or “1”.

- Operations that can be performed on classical bits include flips (NOT) and comparisons (AND and OR).

Quantum computers utilize the unique features of qubits, like superposition and entanglement, to process information in ways that can’t be done with classical bits.

- Operations that can be performed on qubits include flips, transformations into superposition states, and creating entanglement between multiple qubits.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will describe how computers function by processing information stored in bits.

QIS Learning Outcome(s)

- Students will identify that quantum computers function by processing quantum information stored in qubits.

(MS.Sci.7.2)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-3 - Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.

MS Science 7.3 — QUANTUM COMPUTING

DESCRIPTION

Quantum computers have unique engineering challenges.

Qubits cannot be kept in the same state easily due to decoherence.

- Example: An avocado changes state rapidly when interacting with the environment. Similarly, unless they are kept isolated, qubits will change their state and cease to be useful.

The superposition state of a qubit needs to be precisely controlled, while transforming a classical bit to a “0” or “1” can be accomplished more easily.

Scaling from small quantum computers to larger useful devices brings its own series of challenges, such as connectivity and fabrication.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to describe the challenges and complexities of building computers.

QIS Learning Outcome(s)

- Students will identify some of the engineering challenges of building quantum computers and quantum information technology.

(MS.Sci.7.3; same as MS.CS.7.3)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-4 - Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

MS Computer Science 7.1 — QUANTUM COMPUTING

DESCRIPTION

Computers of today are used to solve problems that have changed our lives in many ways, but there are some problems that are too difficult for even the most powerful supercomputers.

Quantum computers of the future can be used to solve some problems much more efficiently than traditional computers.

- Quantum computers are able to factor large numbers very efficiently, with applications in cryptography and internet security.
- Quantum computers can be used to simulate the physics and chemistry of the world around us, with potential applications in drug design, medical technology, materials science, fertilizer development, and more.

Quantum computers are special-purpose devices that will work alongside traditional methods of computing.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to describe how the development of computers in the 1900s enabled the development of many modern technologies.

QIS Learning Outcome(s)

- Students will identify how future societal advancements will arise from the development of new technologies like quantum computing.

(MS.CS.7.1; same as MS.Sci.7.1)

STANDARDS ALIGNMENT

CSTA:

- 1B-IC-18 - Discuss computing technologies that have changed the world, and express how those technologies influence, and are influenced by, cultural practices.
- 3A-IC-24 - Evaluate the ways computing impacts personal, ethical, social, economic, and cultural practices.
- 3B-IC-26 - Evaluate the impact of equity, access, and influence on the distribution of computing resources in a global society.

MS Computer Science 7.2 — QUANTUM COMPUTING

DESCRIPTION

Traditional computers process information stored in classical bits, which can take the value of “0” or “1”.

- Operations that can be performed on classical bits include flips (NOT) and comparisons (AND and OR).

Quantum computers utilize the unique features of qubits, like superposition and entanglement, to process information in ways that can’t be done with classical bits.

- Operations that can be performed on qubits include flips, transformations into superposition states, and creating entanglement between multiple qubits.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will describe how computers function by processing information stored in bits.

QIS Learning Outcome(s)

- Students will identify that quantum computers function by processing quantum information stored in qubits.

(MS.CS.7.2)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

CSTA:

- 2-DA-07 - Represent data using multiple encoding schemes.
- 3A-CS-02 - Compare levels of abstraction and interactions between application software, system software, and hardware layers.

MS Computer Science 7.3 — QUANTUM COMPUTING

DESCRIPTION

Quantum computers have unique engineering challenges.

Qubits cannot be kept in the same state easily due to decoherence.

- Example: An avocado changes state rapidly when interacting with the environment. Similarly, unless they are kept isolated, qubits will change their state and cease to be useful.

The superposition state of a qubit needs to be precisely controlled, while transforming a classical bit to a “0” or “1” can be accomplished more easily.

Scaling from small quantum computers to larger useful devices brings its own series of challenges, such as connectivity and fabrication.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to describe the challenges and complexities of building computers.

QIS Learning Outcome(s)

- Students will identify some of the engineering challenges of building quantum computers and quantum information technology.

(MS.CS.7.3; same as MS.Sci.7.3)

MS Computer Science 7.4 — QUANTUM COMPUTING

DESCRIPTION

Quantum computers will be able to solve certain problems in much less time than on a classical computer.

We can compare the run-time of algorithms that can be run on a classical computer and quantum computers by visualizing the graphs and comparing their rates of growth.

- For factoring large numbers, the run-times of classical algorithms grow exponentially and quantum algorithms grow much slower.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to analyze the worst case run-time of different algorithms and argue about the reasonableness of a solution.

QIS Learning Outcome(s)

- Students will understand that certain problems can be solved much faster on quantum computers than on classical computers.

(MS.CS.7.4)

STANDARDS ALIGNMENT

CSTA:

- 1B-AP-08 - Compare and refine multiple algorithms for the same task and determine which is the most appropriate.
- 3B-AP-11 - Evaluate algorithms in terms of their efficiency, correctness, and clarity.

MS Computer Science 7.5 QUANTUM COMPUTING

DESCRIPTION

Computer programmers design algorithms for solving computational problems. They look for properties or aspects of their problem that will allow them to develop more efficient algorithms to solve their problem.

Quantum computers store and process information using qubits. The unique features of quantum bits compared to classical bits allows quantum computers to solve certain problems faster than classical computers.

- For example, a quantum computer can store the state of a quantum system, such as an atom or a molecule, more efficiently than a classical computer. This property of quantum computers will allow them to simulate quantum systems more efficiently and accurately than classical computers.
- For example, qubits can exist in a superposition of multiple quantum states and process computations in parallel. For certain computational problems, such as factoring large numbers, quantum computers can take advantage of this property of quantum bits to gain a speed advantage over classical computers.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will be able to identify properties of a problem that allow for more efficient solutions/ algorithms.

QIS Learning Outcome(s)

- Students will be able to identify properties of a problem that allow for more efficient solutions for problems that quantum computers are expected to solve more efficiently.

(MS.CS.7.5)

8. QUANTUM COMMUNICATION

KEY CONCEPT

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.

MS Science 8.1 QUANTUM COMMUNICATION

DESCRIPTION

Cryptography used in many online systems today relies on mathematical problems that are difficult for even super-computers to solve. However, some of the underlying assumptions of these algorithms essential for their security would not remain true against future quantum computers.

Quantum key distribution (QKD) allows us to generate shared keys to encrypt information, where the security is guaranteed not by mathematics but by the physics of the protocol.

The main quantum principle used in QKD is that the quantum state is generally changed when it is measured. If an eavesdropper measures a signal encoded in a quantum state, it will change the state. A particular set of quantum states and measurements can be used to detect the presence of an eavesdropper.

Various protocols for quantum cryptography use quantum features like superposition and entanglement to improve their security.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will demonstrate how cryptography is used in many kinds of communications, especially over the internet, to keep our information safe and secure from hackers.

QIS Learning Outcome(s)

- Students will identify how quantum cryptography allows us to encrypt and decrypt information with security guaranteed by the laws of physics.

(MS.Sci.8.1)

POSSIBLE ACTIVITIES

1. Students can use the one-time pad protocol to encrypt and decrypt information using a secret key. They may generate the keys using a QKD simulator or demonstration if available.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-2 - Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.
- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS Science 8.2 QUANTUM COMMUNICATION

DESCRIPTION

In telecommunications, many different wavelengths of light are used for different purposes.

- Radio waves are used for medium-distance broadcasting purposes.
- Infrared light and visible light are used for fiber-optic communication and satellite communications.

In quantum communication, different wavelengths of light can be used to build quantum networks with different technologies.

- Infrared light between 1300-1550 nm in wavelength is used in fiber-optic communication to distribute photons in city-scale networks.
- Visible and near-infrared photons between 800-1500 nm are used in free-space communication, such as from Earth to orbiting satellites.
- Quantum networks can be used to distribute qubits and quantum states for quantum cryptography and to connect distant quantum devices.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will demonstrate that different regions of the electromagnetic spectrum are used for different tools and technologies.

QIS Learning Outcome(s)

- Students will identify that photons in certain regions of the electromagnetic spectrum are useful for both classical and quantum communication.

(MS.Sci.8.2)

POSSIBLE ACTIVITIES

1. Students will compare and contrast various ways to encode information as bits using any physical objects they can imagine, learning that information must be stored in a physical system. They can then find the strengths and weaknesses of various encodings. They can extend this analysis to quantum bits.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-2 - Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.
- MS-PS4-3 - Integrate qualitative scientific and technical information to support the claim that digitized signals are a more reliable way to encode and transmit information than analog signals.
- MS-ETS1-1 - Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.

MS Computer Science 8.1 QUANTUM COMMUNICATION

DESCRIPTION

Cryptographic technology allows people to communicate private information over the Internet, such as banking or e-commerce transactions.

Much of the current technology that we use for sending private information over the Internet is based on the difficulty for classical computers to solve certain computational problems, such as factoring very large numbers.

Quantum cryptography is an approach to privacy that is based on the laws of physics.

- One of the basic properties of quantum measurements is that measurement itself will change the quantum state being measured.
- Some approaches to communicating private information using quantum technology, such as BB84, are based on this property of quantum measurements.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will explain how people communicate very important, private information over the internet.

QIS Learning Outcome(s)

- Students will identify how quantum cryptography allows us to encrypt and decrypt information with security guaranteed by the laws of physics.
- Students will discuss the fact that measurements can affect quantum states, allowing us to detect whether someone has read the private information encoded and communicated using quantum states.

(MS.CS.8.1)

STANDARDS ALIGNMENT

CSTA:

- 1B-NI-05 - Discuss real-world cybersecurity problems and how personal information can be protected.
- 2-NI-05 - Explain how physical and digital security measures protect electronic information.
- 2-NI-06 - Apply multiple methods of encryption to model the secure transmission of information.

9. QUANTUM SENSORS

KEY CONCEPT

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.

MS Science 9.1 — QUANTUM SENSING

DESCRIPTION

Traditional sensors may be built in many ways.

- A thermometer measures temperature by seeing how a material expands.

Quantum sensors use systems that obey the rules of quantum mechanics.

- Lasers can be used as quantum sensors by using wave interference, as applied in medical imaging and gravitational wave observation.
- The quantum properties of atomic nuclei can be measured in magnetic resonance imaging (MRI) machines to see inside a human body.
- Magnetic fields can be measured precisely using superconductors in electroencephalogram (EEG) machines.

Quantum sensors reach the ultimate level of measurement precision allowed by nature and can be used to define important units, including SI units.

- The color of light emitted by Cesium atoms in a particular quantum state is used to define the duration of one second, as applied in very accurate atomic clocks.
- The length of one meter is defined relative to the atomic clock standard and the speed of light.
- The weight of one kilogram is defined relative to Planck's constant, a fundamental quantum constant that can be measured precisely with quantum sensors.

The degree of precision we need varies for different activities.

- We can keep track of time for everyday purposes using a watch accurate to the minute. A stopwatch may need to be accurate to 1/100 of a second for sports events. For global positioning system (GPS) coordination, timing accuracy at the level of a few billionths of a second is needed.

LEARNING OUTCOMES

CS Learning Outcome(s)

- Students will use sensors to measure physical properties of the world.
- Students will describe how sensors measure something about the world based on how it interacts with another, more well-understood system.

QIS Learning Outcome(s)

- Students will describe how quantum sensors use quantum effects like superposition, interference, and entanglement to precisely measure certain properties.

(MS.Sci.9.1)

POSSIBLE ACTIVITIES

1. Students can measure interference from a laser beam illuminating a human hair and use the interference pattern to estimate the width of their hair.

STANDARDS ALIGNMENT

NGSS:

- MS-PS4-2 - Develop and use a model to describe that waves are reflected, absorbed, or transmitted through various materials.
- MS-ETS1-1 - Define the criteria and constraints of a design problem with sufficient precision to ensure a successful solution, taking into account relevant scientific principles and potential impacts on people and the natural environment that may limit possible solutions.
- MS-ETS1-2 - Evaluate competing design solutions using a systematic process to determine how well they meet the criteria and constraints of the problem.
- MS-ETS1-3 - Analyze data from tests to determine similarities and differences among several design solutions to identify the best characteristics of each that can be combined into a new solution to better meet the criteria for success.
- MS-ETS1-4 - Develop a model to generate data for iterative testing and modification of a proposed object, tool, or process such that an optimal design can be achieved.

QIS KEY CONCEPT & NGSS CONNECTIONS

Below, you will find a summary of the topics in the QIS framework for middle-school science, along with relevant keywords and potential links to the Next Generation Science Standards (NGSS).

Please note that the links to NGSS are forward-looking and meant to serve as conversation starters for the development of curricular activities. This framework is an invitation for collaboration between educators and researchers for developing these curricular activities and lesson plans.

QIS Topic / Concept	Short Description	QIS Key Concept	NGSS Connection
1. Quantum Information Science	Career opportunities in QIS	MS.1.1	
2. Quantum State	Using the state of a system to make predictions	MS.Sci.2.1	
3. Measurement	Measurements in quantum are probabilistic	MS.Sci.3.1	MS-ETS1-3
	Measurements change the state of the system	MS.Sci.3.2	
4. Qubit	Classical and quantum bits	MS.Sci.4.1	MS-PS4-3 MS-ETS1-2
	Atomic qubits	MS.Sci.4.2	MS-PS1-1 MS-PS4-3 MS-ETS1-2
	Photonic qubits	MS.Sci.4.3	MS-PS4-1 MS-PS4-2 MS-PS4-3 MS-ETS1-2
	Quantum circuits	MS.Sci.4.4	MS-PS2-3 MS-PS4-3 MS-ETS1-2
5. Entanglement	Conservation laws	MS.Sci.5.1	MS-PS3-4
6. Decoherence	Disturbance from outside influences	MS.Sci.6.1	MS-ETS1-1
	Natural lifetimes of qubits	MS.Sci.6.2	MS-ETS1-1
	Engineering robust qubits	MS.Sci.6.3	MS-ETS1-1 MS-ETS1-2 MS-ETS1-3 MS-ETS1-4
7. Quantum Computing	Potential impact of quantum computing	MS.Sci.7.1	MS-PS1-3 MS-PS4-3 MS-ETS1-2 MS-ETS1-3
	Processing bits vs. qubits	MS.Sci.7.2	MS-PS4-3 MS-ETS1-2 MS-ETS1-3
	Engineering challenges of quantum computing	MS.Sci.7.3	MS-PS4-3 MS-ETS1-2 MS-ETS1-4
8. Quantum Communication	Keeping information secure using quantum key distribution	MS.Sci.8.1	MS-PS4-2 MS-PS4-3 MS-ETS1-2
	Transmitting information as photons	MS.Sci.8.2	MS-PS4-2 MS-PS4-3 MS-ETS1-1 MS-ETS1-2
9. Quantum Sensing	Using quantum sensors to make precise measurements	MS.Sci.9.1	MS-PS4-2 MS-ETS1-1 MS-ETS1-2 MS-ETS1-3 MS-ETS1-4

GLOSSARY

Bits (binary digits)

A binary digit, or bit, is the fundamental unit of classical information, usually represented as either a “0” or a “1”.

To distinguish from qubits, sometimes bits are referred to as “classical bits” in quantum information science and technology.

Bits are encoded in a physical system with two distinguishable states, such as whether a magnetic field is pointed one direction or another in a hard drive.

Classical vs. Quantum

The adjective “classical” is often used in QIS to refer to science and technology that does not rely on quantum mechanics. For example, “classical computing” would describe the types of computers we use today, and “classical physics” would be the branches of physics that do not consider quantum phenomena.

Classical does not imply “completely understood” or “already solved”. There are many open problems in classical physics and classical computing. Quantum science and technology complement these fields and add new challenges and opportunities by considering a broader set of situations and possibilities.

Coherence

Coherence quantifies the wave-like properties of a quantum state.

It is closely related to features and phenomena like superposition and interference.

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

Correlation

Correlation is a relationship between two objects or variables where the state of one is related to the state of the other.

Cryptography

Cryptography is the practice and study of secure communication, where information is hidden from potential eavesdroppers but faithfully transmitted to the intended recipient.

The one-time pad is a specific cryptographic protocol where the information is mixed with a key that is the same length as the message and decrypted by unmixing it. It is a perfectly secure method of encryption, provided the key is secret and used only once.

Decoherence

Decoherence is the process by which qubits are corrupted by interactions with the surrounding environment.

Qubits that have decohered have lost some of their quantum properties, such as superposition and entanglement.

Digital vs. Analog Signals

Digital signals send information as one of a discrete set of possible options. Bits, for example, are digital signals with two possible states.

Analog signals send information within a continuous range of possible values.

GLOSSARY (CONTINUED)

Electromagnetic radiation

Electromagnetic (EM) radiation is a wave of electric and magnetic fields that travels at the speed of light.

Visible light is electromagnetic radiation with a wavelength between 400-800 nm, approximately. Other types of EM radiation include radio waves, microwaves, infrared light, ultraviolet light, x-rays, and gamma rays.

The fundamental unit of electromagnetic radiation is called a photon.

Encoding and decoding

To store information in a computer as a sequence of bits, it must be encoded according to a set of rules.

For example, in ASCII code, the letter “A” is encoded as “0100 0001”. If we know the rules for encoding text, we can also decode the sequence of bits back into text that can be read by humans.

In cryptography, where the information is meant to be kept secret, this is sometimes called encryption and decryption.

Entanglement

Entanglement describes a relationship between multiple qubits in a system, where the outcomes of measurements on separate qubits in the entangled system are correlated.

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

Entanglement is necessary for obtaining a quantum advantage in most QIS applications.

Ground state

The ground state is the lowest energy state of a quantum system, like an atom. Higher-energy states are called excited states.

Generally, the ground state is the most stable state for the system to be in.

Most systems, over time, will transform or decay from excited states to the ground state.

Photon

A photon is the smallest possible unit of electromagnetic radiation. It has the smallest amount of energy possible and cannot be divided further.

Most sources of light we interact with carry more than a million trillion (1018) photons per second.

Many technologies in QIS require devices that produce photons one at a time, often called single photon sources.

Polarization of light

Polarization is defined by the direction of the electric field of light. While the electric field must be perpendicular to the direction the beam travels, it can be either side-to-side (horizontal) or up-and-down (vertical).

The polarization of a single photon is a common way to encode a bit into light (for example, horizontal as “0” and vertical as “1”).

Polarizers are materials that absorb light depending on its polarization. They are used in LCD monitors, sunglasses, and more.

If a single photon encounters a polarizer, it is either transmitted or absorbed. This is an example of a quantum measurement.

Birefringent materials are those that can rotate the polarization of light. Many plastics and crystals have this property, which causes them to look multi-colored when viewed through crossed polarizers.

GLOSSARY (CONTINUED)

Probabilistic

Probabilistic processes are those which cannot be predicted with certainty in advance.

Probabilistic processes follow a probability distribution; for example, the result of a (fair) dice roll has a ▯ probability for each possible outcome.

Quantum bits (qubits)

The quantum bit, or qubit, is the fundamental unit of quantum information.

It can be encoded in a physical system, such as polarization states of light, energy states of an atom, or spin states of an electron.

Usually, one state of the qubit is labeled “0” and another distinguishable state is labeled “1”, in analogy with classical bits.

Unlike a classical bit, a qubit can be in a superposition state and entangled with other qubits.

Quantum communication

Quantum communication is the transfer of quantum states between different locations.

Quantum communication can use a transmission channel (such as an optical fiber) or entanglement to accomplish this goal.

Quantum computer

Quantum computers use qubits and quantum operations instead of classical bits and classical operations to process information.

Quantum computers will solve certain complex computational problems more efficiently than classical computers.

Quantum error correction

Quantum error correction is a method of keeping qubits from decohering in quantum computers.

Quantum information science (QIS)

Quantum information science exploits quantum principles to transform how information is acquired, encoded, manipulated, and applied.

Quantum information science encompasses quantum computing, quantum communication, and quantum sensing.

Quantum key distribution (QKD)

Quantum key distribution is a method of implementing cryptography based on quantum physics principles.

Due to the fragility of quantum systems, an eavesdropper’s interloping measurement will almost always be detected.

Quantum measurement

A quantum measurement informs an observer of what quantum state the system is in out of a set of possible outcomes.

Quantum measurements are unlike classical measurements because the outcome may not be perfectly predictable, even if the quantum state before the measurement is perfectly known.

GLOSSARY (CONTINUED)

Quantum sensing

Quantum sensing uses quantum states to detect and measure physical properties with a higher precision than possible with classical sensors.

Quantum state

A quantum state is a mathematical representation of a physical system, such as an atom, that obeys the rules of quantum mechanics.

Superconductors

A superconductor is a material that has zero electrical resistance, meaning that current flows freely without losing energy to heat.

Materials must be cooled to very cold temperatures to become superconductors.

Superposition

A superposition state is a combination of multiple distinguishable quantum states.

When measured, a superposition state will be found in one of the distinguishable states probabilistically.

As an example, a qubit can be in the “0” state, the “1” state, or a superposition of both “0” and “1”.

Uncertainty

The outcome of a measurement is uncertain if it cannot be perfectly predicted before the measurement takes place.

Classical uncertainty usually arises from ignorance about the details of a system, such as not being able to accurately model every force on a coin while it is flipped.

The outcomes of quantum measurements can be fundamentally uncertain. Even if we perfectly know the quantum state, we may not be able to perfectly predict the measurement outcomes.

Wave-particle duality

Wave-particle duality describes how quantum objects cannot be neatly classified as either waves or particles. Objects like photons, electrons, and atoms have some properties that are usually associated with particles (such as being countable or discrete) and other properties that are usually associated with waves (such as interference and superposition).