QIS Key Concepts for K-12 Physics

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 Physics Focus Group

Quantum information science leverages quantum mechanics to develop new capabilities in computing, sensing, and communications. In many physics classes, there may be natural points of integration around topics such as modern physics, electricity and magnetism, properties of light, and circuits. The purpose of the QIS K-12 Key Concepts Physics 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 physics lessons and activities for teaching QIS K-12 Key Concepts.

The focus group brought together a range of experts, including educators familiar with both teaching and research of physics concepts at high school and/or university levels. The members were:

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*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. The group also drafted cross-cutting themes (pg. 28) and identified tie-ins to current NGSS standards (pg. 32). This information is listed at the end of the document. This initial framework is intended to evolve over time as quantum education for K-12 develops.

References

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1. QUANTUM INFORMATION SCIENCE

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.

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**.**

- Quantum states are represented by directions or vectors in an abstract space.
- 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.
- 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. *[see section on Coherence]*

Summary Description: A quantum state is a mathematical representation of the properties of a physical quantum system, and contains the information needed to predict the outcomes of experiments.

Expectation: Students will be able to identify quantum systems and their distinguishable states, and recognize that these states can exist in superposition.

Learner Outcomes

1. Students will be able to identify physical systems that are described by quantum mechanics (referred to as “quantum systems”).
    a. Example: To predict the behavior of fundamental particles, such as electrons, as well as atoms and molecules, we require a mathematical description beyond classical mechanics.
    b. Example: Electromagnetic radiation consists of indivisible units, or quanta, of energy called photons.
    c. Example: Light interacts with atoms in a way that cannot be fully described by classical physics (e.g., the photoelectric effect, atomic spectra). Quantum mechanics is a better theory to explain these interactions.
2. Students will describe that many properties of quantum systems are quantized, meaning that they are restricted to discrete values, and explain experimental evidence for quantization.
    a. Example: The photoelectric effect demonstrates that electromagnetic radiation consists of indivisible units, or quanta, of energy called photons.
    b. Example: In an atom, the energy levels of its electrons are quantized, as demonstrated in spectroscopy experiments.

    c. Example: The spin magnetic moment of an electron is either up or down, as demonstrated by the Stern-Gerlach experiment.
3. Students will identify that quantum systems have states that are distinguishable (or mutually exclusive) from each other.
    a. Example: A photon's polarization has pairs of mutually-exclusive states, such as horizontal and vertical.
    b. Example: An electron's spin has pairs of mutually-exclusive states, such as spin-up and spin-down.
    c. Example: An atom has an infinite number of mutually-exclusive states with different energies (commonly called energy levels).
4. Students will explain that quantum states can be expressed as superpositions of multiple distinguishable states. Students will connect the idea of superposition to vectors that are expressed as combinations of basis vectors.
    a. Example: A photon's polarization state can be expressed in terms of horizontal and vertical components, or in any other (orthogonal) basis consisting of two perpendicular polarizations.
    b. Example: An electron bound to an atom can be in a superposition of different energy states.
    c. Example: A particle, such as an electron, passing through two slits in a double-slit experiment results in interference. The distinguishable quantum states correspond to the particle passing through one slit or the other. Interference arises when the quantum state of the particle has components corresponding to both.
    d. **Honors/AP Extension**: Students will be able to represent quantum states in an abstract space as column vectors with complex entries (probability amplitudes) in a given basis.
        i. Example: A photon with horizontal polarization can be represented by a column vector [1,0], and a vertical polarization can be represented by a column vector [0,1]. Then, a 45° polarization can be represented by a column vector $[1/\sqrt{2},\ 1/\sqrt{2}]$ and a -45° polarization can be represented by a column vector $[1/\sqrt{2}, -1/\sqrt{2}]$.
        ii. Example: An spin-up electron can be represented by a column vector [1,0], and a spin-down electron can be represented by the column vector [0,1]. Then, a spin-left electron can be represented by a column vector $[1/\sqrt{2},\ 1/\sqrt{2}]$, and a spin-right electron can be represented by a column vector $[1/\sqrt{2}, -1/\sqrt{2}]$.
    e. **Honors/AP Extension**: Students will be able to write quantum states in matrix form and Dirac notation, including specific examples such as polarization states and spin states.
        i. Example: In Dirac notation, a photon with horizontal polarization can be represented by the ket $|H>$, and a photon with vertical polarization can be represented by the ket $|V>$. Then, a 45° polarization can be written as

$(1/\sqrt{2})\ |H> + (1/\sqrt{2})\ |V>$, and a -45° polarization can be written as $(1/\sqrt{2})\ |H> - (1/\sqrt{2})\ |V>$.

ii. Example: In Dirac notation, a spin-up electron can be represented by the ket $|\uparrow>$, and a spin-down electron can be represented by the ket $|\downarrow>$. Then, a spin-left electron can be written as $(1/\sqrt{2})\ |\uparrow> + (1/\sqrt{2})\ |\downarrow>$, and a spin-right electron can be written as $(1/\sqrt{2})\ |\uparrow> - (1/\sqrt{2})\ |\downarrow>$.

f. **Honors/AP Extension**: Students will identify that vectors corresponding to quantum states have a magnitude of one and that distinguishable quantum states corresponding to those with a scalar (inner) product of zero.

i. Example: An electron in a general superposition of spin states can be written as $a^*|\uparrow> + b^*|\downarrow>$, with the coefficients such that $|a|^2 + |b|^2 = 1$.

ii. Example: The horizontal and vertical polarization states are distinguishable, and the vectors representing them have an inner product of zero ($<V|H> = 0$).

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 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)*
- A quantum state determines the probability of the outcome of a single quantum measurement, but one outcome rarely reveals complete information about the system.
- Repeated measurements on identically prepared quantum systems are required to determine more complete information about the state.
- Because of the limitations of quantum measurement (providing only partial information and disturbing the system), quantum states cannot be copied or duplicated.

Summary Description: In general, the outcomes of quantum measurement are not predetermined. The probabilities of each outcome depends on the quantum state and choice of measurement basis.

Expectation: Students will be able to calculate the probability of obtaining different measurement outcomes, and describe how that probability changes when the measurement basis changes.

Learner Outcomes

1. Students will be able to contrast classical and quantum measurements.
    a. Example: Repeated classical measurements should give the same result. In contrast, quantum measurements on identically prepared systems can give random results from a set of possible outcomes with probabilities dictated by the quantum state.
2. Students will demonstrate how the probability of measuring a certain outcome depends on both the quantum state and the choice of measurement basis. The choice of measurement basis determines which mutually exclusive quantum states are being distinguished from each other.
    a. Example: If a photon is vertically polarized, it will definitely be found as vertical if measured in the horizontal/vertical basis (e.g., with a vertical polarizer). However, if measured in the +45°/−45° diagonal basis (e.g., by rotating the polarizer), the photon will be found in one of the two diagonal states randomly. This can be used to generate fundamentally random numbers.

b. **Honors/AP Extension**: Given a quantum state, students will be able to apply the Born rule to calculate the probability of measuring different outcomes in different measurement bases.
   i. Example: A photon in a superposition of horizontal and vertical polarizations is written as $a|H> + b|V>$ in Dirac notation. When this photon is measured in the horizontal/vertical basis, it has a probability $|a|^2$ of being measured as horizontal, and $|b|^2$ of being measured as vertical. The quantum state must be normalized such that $|a|^2 + |b|^2 = 1$, to ensure that the sum of all probabilities add up to 1.
   ii. Example: A vertically polarized photon, written in Dirac notation as |V>, will definitely be found in the vertically polarized state when measured with a vertical polarizer, since $|<V|V>|^2 = 1$. However, when measured in the diagonal basis composed of the states $|+> = (|H> + |V>)/\sqrt{2}$ and $|-> = (|H> - |V>)/\sqrt{2}$, it will be found in either |+> or |−> randomly, since $|<+|V>|^2 = |<-|V>|^2 = 1/2$.

3. Students will be able to describe how the choice of measurement basis dictates whether or not a state is represented as a superposition.
   a. Example: A vertically polarized photon is not represented as a superposition in the horizontal/vertical basis, but is represented as a superposition in the +45°/−45° diagonal basis. A +45° polarized photon can be represented as a superposition of horizontal and vertical, but is not represented as a superposition in the +45°/−45° diagonal basis. The choice of representation needed depends on the measurement being performed.
   b. Example: A spin-up electron is always found to be deflected upward in a Stern-Gerlach experiment with magnetic field gradient oriented up/down. Alternatively, it deflects randomly to the left or right when the gradient is oriented left/right because a spin-up electron is a superposition of left and right spins.
4. Students will describe situations where a quantum measurement changes the quantum state.
   a. Example: A photon is blocked by two perpendicular polarizers. Inserting a third polarizer between them at a different angle will allow the photon to pass through all three polarizers with some probability due to the additional measurement.
   b. Example: In a Stern-Gerlach experiment, an electron passing through two up/down-oriented magnetic field gradients will deflect the same way in both. If a gradient oriented left/right is introduced between them, the final deflection will be randomly up or down, independent of the first deflection.
   c. Example: In a double-slit experiment, measuring which slit the photon or electron goes through destroys the interference pattern.
5. Students will explain how multiple measurements on identically prepared systems are required to estimate the probability of measuring different outcomes and reveal interference patterns.

a. Example: To observe the interference pattern in a double-slit experiment, the experiment must be repeated with many individual photons or electrons.
b. Example: If a photon passes through a vertical polarizer, we can only conclude that it is not horizontally polarized. The experiment must be repeated multiple times with photons in the same polarization state to estimate the probability of the photon passing through the polarizer, and determine whether it was initially in a superposition state.
c. **Honors/AP Extension**: Students will be able to calculate the expectation value $< Q >$ of an observable Q (physically measurable quantity) to describe the average outcome of a large number of measurements on identically prepared systems in a certain state.
    i. Example: Taking the sum of the probabilities multiplied by the corresponding measured values gives the weighted average outcome, known as the expectation value.
    ii. Example: If there is a 75% probability of measuring an outcome with a value “ $+1$” and a 25% probability of measuring an outcome with a value “ -1”, the expectation value of the measure is $0.75 - 0.25 = 0.5$.
    iii. Example: If the identically prepared systems are each in the state $|\psi>$, then $< Q > = < \psi|Q|\psi >$.

6. Students will explain that if the outcomes of a measurement of one property can be perfectly predicted, the measurement outcomes of some other properties would be random and unpredictable.
    a. Example: Momentum and position are incompatible properties in a quantum system. This means if we precisely know the position of an electron, we are limited in how precisely we can know its momentum according to the Heisenberg Uncertainty Principle.
    b. Example: For a horizontally polarized photon, a measurement outcome in the horizontal-vertical basis will be perfectly predictable, while a single measurement outcome in the +45°/−45° basis will be completely random.
    c. Example: If we precisely know the value of an electron’s spin in the up/down direction, the value of the spin along the left/right direction is completely unpredictable.
    d. **Honors/AP Extension**: Students will be able to calculate the uncertainty (ΔQ) in an observable as $(\Delta Q)^2 = < Q^2 > - < Q >^2$.
        i. Example: If the identically prepared systems are each in the state |ψ>, then $< Q^2 > = < \psi|Q^2|\psi >$ and $< Q >^2 = (< \psi|Q|\psi >)^2$. The variance is the difference, i.e., $(\Delta Q)^2 = < Q^2 > - < Q >^2$, and the uncertainty (standard deviation) is the square root.

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.

- Unlike a classical bit, each qubit can represent information in a superposition, or vector sum that incorporates two mutually exclusive quantum states.
- 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)*
- Multiple qubits can also be entangled, where the measurement outcome of one qubit is correlated with the measurement outcomes of the others.

Summary Description: The quantum bit, or qubit, is the fundamental unit of quantum information, and it is encoded in a physical system, such as polarization states of light, energy states of an atom, or spin states of an electron.

Expectation: Students will be able to explain how quantum bits differ from classical bits, and to identify physical systems that can be used as quantum bits.

Learner Outcomes

1. Students will describe that the smallest unit of information is a bit, which can be in the state “0” or “1”. Students will identify systems that can store classical bits of information.
    a. Example: A bit has the fewest number of mutually exclusive states (two), and we can represent any classical information as a series of bits.
    b. Example: Voltage across an electronic component below and above a threshold can be used to encode “0” or “1” for classical information processing.
2. Students will identify general quantum systems that can serve as quantum bits (qubits) to encode quantum information.
    a. Example: A qubit can be encoded and transmitted using perpendicular polarization states of a photon. For instance, a “0” can be encoded as horizontal polarization and a “1” as vertical polarization.
    b. Example: The spin state of a single electron can be used to encode a qubit, with “0” corresponding to spin-up and “1” corresponding to spin-down.
    c. Example: Two isolated energy levels of an atom (or any quantum system) can be used to encode a qubit, where “0” corresponds to the lower energy and “1” corresponds to the higher energy.

   d. **Honors/AP Extension**: Students will be able to represent the distinguishable states of qubits mathematically and identify how they are encoded in physical systems.
      i. Example: The spin state of a single electron can be written in Dirac notation with $|0>$ representing the spin-up state and $|1>$ representing the spin-down state, or as a column vector with [1,0] representing the spin-up state and [0,1] representing the spin-down state.
      ii. Example: The state of a qubit can be represented graphically as a point on the Bloch sphere, where mutually exclusive states are 180-degrees apart.
3. Students will distinguish between a classical bit which can only be in the state “0” or “1” and a qubit which can be in the state “0”, “1”, or in a superposition of the states “0” and “1”.
   a. Example: A qubit encoded in the spin of an electron can be in the state “0” (spin-up), the state “1” (spin-down), or in a superposition of the states “0” and “1”.
   b. Example: A qubit encoded in the polarization of a photon can be in the state “0” (horizontal), the state “1” (vertical), or in a superposition of the states “0” and “1” (45° diagonal, for example).
4. Students will describe how measuring a qubit changes (collapses) its state, depending on the measurement basis, and that each measurement results in only one bit of information. In contrast, measuring a classical bit does not change its state.
   a. Example: When a qubit in a superposition of “0” and “1” is measured, the outcome of the measurement will be either “0” or “1” and the qubit will collapse to the corresponding “0” or “1” state.
   b. Example: The possible outcomes of a measurement on a qubit depends upon the choice of measurement basis. For instance, the polarization state of a photon can be measured with a polarizer rotated to any angle, of which there are infinitely many choices corresponding to infinitely many possible measurement bases.
5. **Honors/AP Extension**: Students will be able to express the state of a qubit, including superposition states, using a mathematical description and relate the amplitudes to measurement probabilities.
   a. Example: A qubit in a superposition state $a|0> +b|1>$ has a probability $|a|^2$ of being measured as “0” and a probability $|b|^2$ of being measured as “1”.
   b. Example: Two different qubit states with equal probabilities of being found as “0” or “1” are $|+> = (|0> + |1>)/\sqrt{2}$ and $|-> = (|0> - |1>)/\sqrt{2}$.
   c. Example: The quantum state $(|+> +|->)/\sqrt{2}$ can be expanded in the basis of $|0>$ and $|1>$, and is equal to $|0>$.

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.

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

Summary Description: Entanglement is an inseparable relationship between multiple qubits, and it is a key property of quantum systems for obtaining a quantum advantage in many QIS applications.

Expectation: Students will be able to explain that qubits can be entangled with each other, and exhibit correlations distinct from classical ones.

Learner Outcomes

1. Students will identify that qubits in an entangled pair share an inseparable quantum state and have measurement outcomes that are correlated with each other.
    a. Example: Two qubits may be entangled such that if one is measured to be “0”, the other will always be measured to be “1”, and vice-versa (this is an example of a Bell state).
    b. Example: Two spin qubits may be entangled such that if one is measured to be spin-up, the other will always be measured as spin-down, and vice-versa. Before the measurement, the outcomes are unknown and we cannot know which qubit will be up (or down). After the measurement, the outcomes will be correlated.
2. Students will describe interactions through which multiple quantum objects may become entangled with each other.
    a. Example: Two photons can become entangled with each other by passing through optical elements called beam splitters, or in special (nonlinear) crystals/materials.
    b. Example: A high-energy photon can split into an entangled electron-positron pair.
    c. Example: Two qubits can be entangled by a controlled-NOT operation, which is a two-qubit quantum gate for quantum computing.

3. Students will describe how measuring one qubit in an entangled pair reveals information about the other qubit, no matter how far apart they are.
    a. Example: In certain Bell states, while the outcome of each individual measurement is random, when one qubit is measured to be “0”, the other qubit will with certainty be measured as “1”.
    b. Example: In experiments, entanglement has been demonstrated between photons separated by a long distance.
4. Students will describe that entanglement has instantaneous effects upon measurement, but these effects do not permit information to travel faster than the speed of light.
    a. Example: Measuring one part of an entangled pair instantaneously collapses the other part, but the measurement cannot be used to send a signal faster than the speed of light since the measurement outcomes are random.
    b. Example: Protocols such as quantum state teleportation use entanglement to perform tasks that could not be accomplished classically, but require classical communication to properly function. Such communication cannot happen faster than light.
5. **Honors/AP Extension**: Students will be able to distinguish between states that are entangled and states that are unentangled (separable).
    a. Example: Math expressions that can be factored into functions of single variables are considered “separable”. For example, the expression $(x^2 - 5) * (1/y + 3)$ is separable because it is a function of x (i.e., $x^2 - 5$) times a function of y (i.e., $1/y + 3$). But, the expression $xy + 1/x$ is inseparable since it cannot be written as a function of x times a function of y. Similarly, the quantum state $|0>|1>$ is separable, but the quantum state $(|0>|1> - |1>|0>)/\sqrt{2}$ is inseparable (entangled).
    b. Example: Changing the basis we express a quantum state in does not change whether or not it is entangled. The state $(|1>|0> + |1>|1>)/\sqrt{2}$ is not entangled since it can be re-written as $|1>|+>$. However, the state $(|0>|0> + |1>|1>)/\sqrt{2}$ is entangled since it cannot be written in a separable form.
6. **Honors/AP Extension**: Students will contrast correlations that can be observed using quantum entanglement with classical correlations by considering outcomes in different measurement bases.
    a. Example: The two qubits in the Bell state $(|0>|1> - |1>|0>)/\sqrt{2}$ exhibit correlations in the basis made of the states $|0>$ and $|1>$. Noting that $|0> = (|+> + |->)/\sqrt{2}$ and $|1> = (|+> - |->)/\sqrt{2}$, we can rewrite the Bell state as $(|+>|-> - |->|+>)/\sqrt{2}$, showing that the qubits have correlations in the basis made of the states $|+>$ and $|->$ as well.
    b. Example: Any model of quantum entanglement using a classical framework (local hidden variables) will be unable to describe certain experiments, such as the Einstein-Podolsky-Rosen (EPR) paradox or Bell experiments.

c. Example: In some games (such as those performed in Bell experiments) where two players must answer questions without directly communicating with each other, they may win more often than classically predicted using entangled states and measurements in different bases.

6. COHERENCE

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

- 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.
- Some types of qubits are inherently isolated, whereas others require carefully engineered materials to maintain their coherence.
- High decoherence rates limit the length and complexity of quantum computations; implementing methods that correct errors can mitigate this issue.

Summary Description: Decoherence is the process by which superposition and entanglement are degraded through undesired interaction with the surrounding environment.

Expectation: Students will be able to explain how quantum systems can be very vulnerable to noise, and describe the engineering and physics challenges to overcome these issues.

Learner Outcomes

1. Students will identify, in broad terms, the challenges in creating low-noise qubits.
    a. Example: Errors can corrupt the state of a qubit, resulting in information stored in the qubit being lost.
    b. Example: Radiation can interact with an atom, causing the quantum state of the system to change.
    c. Example: Superconducting qubits interact with background microwave radiation, and this can result in unintended changes to the quantum state of the qubits.
    d. Example: A qubit must be protected from the environment to avoid unintended errors, yet connected to the environment to be initialized, manipulated, and measured. These competing goals are a challenge in manufacturing qubits.
2. Students will explain that a small change to a qubit or quantum device can result in errors, whereas a large change is needed to corrupt a classical bit.
    a. Example: A classical bit can only be corrupted by a complete bit flip, since it can only be in the state "0" or "1." Since the state of a qubit can be a superposition of "0" and "1," a qubit can also be corrupted by a partial bit flip, which affects the superposition.
    b. Example: If a polarization measurement or Stern-Gerlach experiment occurs at an angle that is different from what was intended, the state will collapse to a different one than what was intended, causing a measurement error.
3. Students will describe how quantum bits are sensitive to multiple types of errors.

    a. Example: A qubit can be corrupted by flipping from the “0” state to the “1” state, or by a change in superposition (the “+” state to the “–” state, for example).
    b. Example: A polarized photon could be corrupted if the horizontal polarization state is flipped to vertical, but could be corrupted in another way if the +45° polarization state is flipped to −45°.
4. Students will describe how quantum superposition and entanglement can be lost if information about the quantum state is leaked to the outside environment.
    a. Example: If information about which slit the photon goes through in a double-slit experiment or which path it takes in a Mach-Zehnder interferometer is obtainable, the interference will be lost. These are called “which-way” or “which-path” experiments.
    b. Example: If information is available about whether a qubit is in the “0” or “1” state, it will collapse and lose its superposition. This occurs regardless of whether the information is obtained by a human observer or through other interactions with the environment.
5. Students will compare the challenges of quantum error correction to those of classical error correction.
    a. Example: Both classical and quantum error correcting codes protect against errors by encoding logical bits/qubits across many physical bits/qubits. Classical errors can be diagnosed by reading the bits, but quantum errors require special measurements on multiple qubits to diagnose.
    b. Example: A classical bit can be copied to create backups, but it is impossible to copy a quantum state due to the no-cloning theorem.
    c. **Honors/AP Example**: Quantum error correction must be able to correct both phase- and bit-flip errors. Classical error correction only needs to correct bit-flip errors.
    d. **Honors/AP Example**: Methods from classical error correction, such as the repetition code, cannot be straightforwardly adapted to quantum error correction due to restrictions such as the no-cloning theorem and the collapse of quantum states after a measurement.

7. QUANTUM COMPUTING

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

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

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

Expectation: Students will explain which properties of quantum mechanics allow for a computational advantage and the potential applications and challenges of quantum computing

Learner Outcomes

1. Students will differentiate the properties of classical bits and quantum bits.
    a. Example: Qubits can be kept in superposition states and entangled with one another, unlike classical bits.
    b. Example: There are infinitely many bases in which we can represent a qubit. The outcomes and associated probabilities depend on the measurement basis. In contrast, a classical bit can only be in the state “0” or “1” and can only be measured as “0” or “1”.
    c. Example: Three bits can be in one of eight possible states (000, 001, etc). Three qubits can be in a superposition state of all eight states until measured, represented by eight complex numbers. Four qubits can be in a superposition of sixteen states and five qubits can be in a superposition of thirty-two states.
    d. Example: 2^N (complex) numbers are generally required to represent a quantum state of N qubits. As the number of qubits grows, an exponentially growing number of classical bits are generally required to model the quantum state.
    e. Example: It is impossible to describe even a modest collection of qubits (~300) in the largest classical computers, since it would require storing too many numbers.
    f. **Honors/AP Example**: The state vector for a system with N qubits has a dimension of 2^N. For example, a three-qubit system is represented by a $2^3 = 8$

dimensional complex vector, with basis states $|000>, |001>, etc.,$ and the three-qubit state can be in any superposition of those 8 basis states, e.g., $a|000> +b|001> +c|010> +d|011> +e|100> +f|101> +g|110> +h|111>$, where the coefficients evolve over time.

2. Students will describe what an algorithm is, and how quantum computers run algorithms in fundamentally different ways than classical computers.
    a. Example: Algorithms can be thought of as recipes for processing information and solving problems.
    b. Example: In classical computers, algorithms define how we prepare, manipulate, and measure the states of bits. In quantum computers, quantum algorithms define how we prepare, manipulate, and measure the states of qubits.
    c. Example: Classical computers give definite outputs when they run an algorithm. Quantum computers have outcomes determined by probabilities, and quantum algorithms are used to increase the probability of finding the right answer from all possible outputs.
    d. Example: Quantum algorithms manipulate quantum states involving superposition and entanglement, and they use interference to maximize the probability of finding the right answer. As the number of qubits grows, the number of terms in the multi-qubit superposition grows exponentially, which could contribute to the advantage that quantum computers have for specific tasks.
    e. Example: In the Deutsch-Jozsa problem, the goal is to determine a property of a function. Using a classical computer, solving this problem requires many evaluations of the function.Using a quantum computer, the problem can be solved using only one evaluation of the function.
3. **Honors/AP Extension**: Students will be able to represent quantum algorithms as quantum circuit diagrams. They will also be able to represent quantum gates as matrices that operate on state vectors through matrix multiplication.
    a. Example: A quantum circuit is a diagram representing a quantum program. It depicts how the state of the qubits evolves as gates and measurements are performed on them.
    b. Example: The X gate, also called the NOT gate, is a single-qubit gate that flips the $|0>$ and $|1>$ components. However, it does not have this same effect in other bases (e.g., with the states $|+>$ and $|->$). It is represented by a 2x2 matrix.
    c. Example: The "Z" gate leaves $|0>$ unchanged and applies a phase of -1 to the $|1>$ state, while the "T" gate applies a phase of $e^{(i\pi/4)}$ to $|1>$ instead. A general phase shift gate adjusts the complex phase between the $|0>$ and $|1>$ components.
    d. Example: The Hadamard gate converts the $|0>$ and $|1>$ state to the $|+>$ and $|->$ states, and vice-versa. It is represented by a $2x2$ matrix. A Hadamard gate followed by a measurement in the $0/1$ basis is equivalent to a measurement in the $+/-$ basis.
    e. Example: The controlled-NOT (CNOT) gate is a two-qubit gate that applies a NOT (X) gate to one qubit depending on the state of a second qubit. It is represented by a $4x4$ matrix mathematically.

    f. Example: Applying quantum gates does not destroy information. Any quantum gate is reversible.
4. **Honors/AP Extension**: Students will identify properties of a universal set of quantum gates, from which any quantum circuit can be constructed.
    a. Example: An example of a universal set of gates consists of the CNOT (which produces entanglement), Hadamard (which creates superpositions), and T gates (which adjusts phases). While other universal sets exist, they must all have these same properties.
    b. Example: A universal set of quantum gates cannot be constructed with only single-qubit gates, as there is no way to create entanglement without multi-qubit gates.
    c. Example: A CNOT and two Hadamard gates can be used to construct a controlled-Z gate, which applies a Z gate to one qubit depending on the state of the other qubit.
5. Students will describe potential use cases for quantum computers, and the advantages they can provide over classical algorithms.
    a. Example: Finding the prime factors of large numbers is believed to be exponentially more difficult for classical computers as the number grows in size. By comparison, the difficulty grows at a much more reasonable rate if we are able to use Shor's algorithm on quantum computers.
    b. Example: Quantum computers can be used to simulate complex quantum systems. This can be used to solve problems more efficiently in chemistry, such as finding the energies and structure of atoms and molecules, with potential applications in environmental science, medicine, materials science, agriculture and more.
    c. Example: For search problems where a classical computer must check each item one-by-one, quantum computers can search quadratically faster using Grover's algorithm.
6. Students will explain that quantum computers have limits as to how quickly they can solve problems.
    a. Example: Quantum computers are special-purpose machines that provide a computational speedup that varies depending on the problem that is being solved. They are not suitable for all computational problems and applications.
    b. Example: A quantum superposition can contain information about many potential answers to a problem, but due to quantum state collapse, only one answer can be extracted per run. This is distinct from classical parallel computing, where multiple answers can be obtained simultaneously.
    c. **Honors/AP Example**: A quantum search algorithm can find a solution in the square root of the amount of time that a classical algorithm takes. For problems where the time needed grows exponentially with the size of the system, the speed-up from the quantum search algorithm will not be sufficient to solve the problem in a reasonable amount of time.
7. Students will describe different physical systems that can be used to build quantum computing devices.

    a. Example: The energy states of a variety of atoms can be used as qubits. In these systems, atoms are isolated and manipulated with laser beams to process quantum information or simulate other quantum systems.
    b. Example: Cryogenically cooled circuits made of superconducting material can be used as qubits. In these systems, physical attributes of the circuit are manipulated using microwaves to process quantum information and simulate other quantum systems.
    c. Example: Qubits can be encoded in various quantum states of light. Optical elements, such as beam splitters are used to process quantum information.
8. Students will describe the engineering challenges faced in building large-scale quantum computers.
    a. Example: Modern quantum computing devices have many sources of noise, including decoherence, imprecise control, and readout errors.
    b. Example: Minimizing decoherence is the major challenge for building quantum computers with many qubits. Quantum error correcting codes can protect against decoherence but require complex measurements and many additional qubits.
    c. Example: Building a quantum computer requires precise control of the qubits' quantum state, which are encoded in fragile physical systems that are susceptible to noise.
    d. Example: Quantum computers require qubits that are both strictly isolated from each other and able to be entangled with each other. Controlling isolated systems is difficult, and that difficulty increases as the number of qubits increases.

8. QUANTUM COMMUNICATION

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

- 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.
- 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.

Summary Description: Quantum communication uses entanglement or a transmission channel to transfer quantum information between different locations.

Expectation: Students will be able to describe (1) how quantum key distribution can be used to securely establish shared secret keys, (2) how quantum information can be transferred through physical channels, and (3) how quantum information can be teleported using entanglement.

Learner Outcomes

1. Students will be able to describe the context and procedure of a quantum key distribution protocol (such as BB84), which solves the classical problem of generating secure secret shared keys.
    a. Students will be able to distinguish between a message (plaintext), a key, and an encrypted message (ciphertext).
    b. Students will explain how a message can be securely sent over a public channel by encrypting and decrypting it using a shared secret key.
        i. Example: The one-time pad protocol uses a secret key made up of random shared numbers to encrypt and decrypt a message.
        ii. Example: Eavesdroppers are able to see encrypted messages but are unable to decrypt them without the secret keys.
    c. Students will be able to explain how two parties are only guaranteed to obtain the same outcome when measuring a qubit if they measure in the same basis.
        i. Example: If a sender (Alice) measures a photon in the horizontal/vertical basis, and then a receiver (Bob) measures the same photon in the same basis, they will get the same outcome.
        ii. Example: If a sender (Alice) measures a photon in the horizontal/vertical basis, and then a receiver (Bob) measures the same photon in the diagonal basis, they may get different outcomes.
    d. Students will describe how, in general, the state of a qubit can change when measured and cannot be copied (cloned).

        i. Example: If a horizontally polarized photon is measured in the diagonal basis and then measured in the horizontal/vertical basis, it will not necessarily be horizontally polarized anymore.
        ii. Example: The no-cloning theorem forbids a general unknown quantum state from being copied. In contrast, classical bits can be copied without disturbing or destroying the original bits.
    e. Students will explain that the sender and receiver must share classical information with each other in order to extract a secret key from their qubit transmission process.
        i. Example: In BB84, the sender and receiver must share the bases they used for each preparation/measurement with each other. This reveals no information about the secret key to an eavesdropper.
    f. Students will explain that if an eavesdropper (often referred to as Eve) intercepts and measures a qubit in a different basis from the sender/receiver, it can cause the sender and receiver's measurement results to differ, which may allow them to identify that the eavesdropper has measured the qubit.
        i. Example: If the sender/receiver and eavesdropper all choose their bases randomly, each bit of the sender and receiver's keys has a 25% probability of disagreeing. If the generated key is very long, the eavesdropper is statistically guaranteed to introduce many errors.
        ii. Example: The sender and receiver can estimate the number of errors in the key by comparing a small section of the key or using a parity check. They can use the error estimated to identify whether an eavesdropper could have compromised their key generation.
    g. Students will explain which properties of quantum information allow for quantum key distribution to have advantages over classical techniques.
        i. Example: BB84 relies on the ability to prepare and measure qubits in multiple bases.
        ii. Example: Quantum key distribution would not work if it were possible to copy an arbitrary quantum state, as the eavesdropper could make many copies of each qubit and determine their quantum states.
2. Students will recognize the emerging opportunities and challenges of building long-distance quantum networks, such as a quantum internet.
    a. Example: One way to send photons over long distances is to use optical fibers. However, many will be lost due to absorption. Unlike classical fiber optic communications, photons cannot be amplified to account for this loss.
    b. Example: Quantum networks that can transmit photons would allow users to perform quantum key distribution to securely communicate and distribute entangled qubits.
3. Students will be able to explain the ideas of quantum teleportation, and describe that the information in the quantum state is what is teleported.
    a. Students will contrast the challenges of transferring quantum information between systems compared to classical communication.

        i. Example: Qubits encoded in trapped atoms cannot be transported by physically moving the atoms out of the trap, but must have their quantum information transported using other systems, such as photons.
        ii. Example: Quantum information cannot be cloned. It is not possible to keep a backup copy in case a qubit is lost during transmission.
    b. Students will describe how an unknown quantum state can be teleported using an entangled state and two classical bits of communication, which destroys the original quantum state in the process.
        i. Example: Alice and Bob share an entangled pair of qubits, and Alice has a separate qubit whose unknown quantum state she wishes to send to Bob; there are three qubits in total. If Alice then measures her two qubits, destroying her original quantum states, and tells Bob the result of her measurement, Bob can apply appropriate quantum gates to his qubit to match the state of the original qubit that Alice wanted to send. Here, entanglement provides an efficient portal for transporting quantum information, but not matter.
    c. **Honors/AP Extension**: Students will be able to draw the quantum circuit for teleportation and show the effects of each operation by expressing how the quantum state of the three qubits changes throughout the protocol.
        i. Example: At the start of the protocol, Alice has an unknown qubit in the state $a|0>+b|1>$ that she wishes to teleport to Bob and Alice and Bob share an entangled state $(|00>+|11>)/\sqrt{2}$. The three-qubit state is $(a|0>+b|1>)(|00>+|11>)/\sqrt{2}$.
    d. Students will identify that the quantum teleportation protocol teleports the state of the qubit rather than the matter, and it does not allow for cloning quantum states or faster-than-light communication.
        i. Example: In the quantum teleportation protocol, Alice must tell Bob the result of her measurement. This classical communication cannot be transmitted faster than the speed of light.
        ii. Example: The original qubit state that Alice teleported to Bob is destroyed during the quantum teleportation protocol, leaving Bob with the only copy of the state.
4. Students will explain how quantum communication protocols often rely on shared entanglement.
    a. Example: Quantum teleportation can be used to transmit the state of a qubit using two classical bits and shared entanglement. Even if the qubit state was known beforehand, it would take many more classical bits to share its precise quantum state.
    b. **Honors/AP Example**: In the superdense coding protocol, if they use a pair of entangled qubits, Alice can send two bits of classical information to Bob by only sending one qubit.

9. QUANTUM SENSORS

Key Concept:
Quantum sensing uses quantum states to detect and measure physical properties with the highest precision allowed by quantum mechanics.

- 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.
- 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.
- 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.

Summary Description: Quantum sensing uses quantum states to detect and measure physical properties with the highest precision allowed by quantum mechanics.

Expectation: Students will describe how quantum principles provide opportunities and set limits for sensing and measurement technologies, and identify how they can be applied in real-world examples.

Learner Outcomes

1. Students will describe how quantization (such as the discretization of energy levels) has been used to develop many sensing and measurement technologies used today.

    a. Example: Materials contain spin-½ particles, such as electrons, that respond to electromagnetic fields. The response changes depending on the material (e.g., types of human tissue), and is used in nuclear magnetic resonance (NMR) and magnetic resonance imaging (MRI) technologies.
    b. Example: Lasers are used in many sensing, measurement, and computing technologies. Lasers generate coherent light, which is amplified by stimulating the emission of photons from the quantum energy states within material/substance.
    c. Example: The precise transitions of electrons between energy levels in an atom can be harnessed as time-keeping devices called atomic clocks.

    d. Example: The quantum energy structure of semiconductors can be used to build light sensors that are able to detect single photons.
2. Students will explain how quantum sensors use interference between quantum states to measure the properties of objects with which they interact.
    a. Example: Interferometers, such as the Mach-Zehnder Interferometer, split a photon's quantum state into multiple paths, one of which goes through an object. By recombining those paths and observing the interference, they can be used to measure properties of the object very sensitively, such as its thickness or index of refraction.
    b. Example: Interferometers built with atoms instead of light can very sensitively measure acceleration, owing to their small effective (de Broglie) wavelengths. This quantum effect can be used in gravitometers for navigation and subsurface exploration.
    c. Example: Superconducting quantum interference devices (SQUIDs) use interference between different quantum states in a superconducting loop to sensitively measure magnetic fields, such as to measure brain activity in electroencephalogram (EEG) machines. SQUIDs also find use in quantum information devices.
3. Students will apply the Heisenberg Uncertainty Principle to explain tradeoffs between how precisely we can simultaneously measure two incompatible properties, such as position and momentum.
    a. Example: Geometry (area) can be used to describe the tradeoff in smallest limits of the uncertainty principle.
    b. Example: Electron beam microscopes use high-speed electrons with a large uncertainty in momentum, which allows for more precise positioning than is possible with visible light.
    c. Example: High-precision atomic clocks require very precisely defined frequencies. With a precisely known frequency, a second can be defined in relation to the electromagnetic wave frequency that causes the atom's electrons to transition between energy states. A precise frequency means that each electron transition has a very precisely defined energy, and due to the energy-time uncertainty relationship, there is a large uncertainty in when each electron will decay because the atomic lifetime of the transition is very long. This is because timing is defined with respect to a frequency (in this case, the frequency of the resonant EM field), which implies the timing of the electron decay itself has a large quantum uncertainty.
    d. Example: Squeezed states are engineered to have a high uncertainty in one property (for example, position), allowing improved precision when measuring the other (for example, momentum). Squeezed states of light can be used to reduce noise in interferometers, including the Laser Interferometer Gravitational-Wave Observatory (LIGO).

4. **Honors/AP Extension:** Students will use the mathematical representation of the Heisenberg Uncertainty Principle as $\Delta x \Delta p \geq \hbar/2$ to make predictions or to explain

experimental results.

   a. Example: The Heisenberg Uncertainty Principle can be used to predict the spreading of a photon's quantum state after passing through a narrow slit, and mimicked in class with laser pointers.
   b. Example: As your knowledge about the position becomes more precise (Δx decreases), the momentum distribution becomes less certain (Δpincreases), such that their product is greater than or equal to $\hbar/2$.

5. Students will describe how quantum measurements can be used to define fundamental constants and units.
   a. Example: One second is currently defined as the time that elapses during 9,192,631,770 transitions in a Cesium-133 atomic clock.
   b. Example: One meter is defined as the amount of distance that light travels in vacuum during 9,192,631,770 transitions in a Cesium-133 atomic clock.
   c. Example: One kilogram is defined relative to Planck's constant, a defined fundamental constant with units of kg*m^2/s. Since the meter is defined relative to the speed of light and the second is defined relative to Cesium-133 atomic clocks, a unit of mass such as the kilogram can be defined relative to Planck's constant, the speed of light, and the transition time of the Cesium-133 atomic clock.

Examples of Physics Crosscutting Themes

Regarding connections to NGSS, the working group drafted cross-cutting theme information specific to quantum information science https://ngss.nsta.org/crosscuttingconceptsfull.aspx. Below, each NGSS cross-cutting theme is listed. The blue text is the output from the working group related to each theme.

1. Patterns:
Observed patterns in nature guide organization and classification and prompt questions about relationships and causes underlying them.
(a) A pattern that occurs across many quantum systems is that they can only exist in a discrete (quantized) set of states, such as atomic energy levels, electron spin states, and photon polarization states.
(b) Periodic patterns are an important feature in quantum information, appearing in interference experiments and many quantum algorithms.
(c) A pattern among quantum algorithms and protocols is that they use features like superposition and entanglement, distinguishing them from their classical equivalents.
(d) Patterns that are similar among both classical and quantum computers are that they must be able to:

- Encode information in a physical system
- Initialize the physical systems
- Transform the information
- Measure the information as an output or result

(e) Patterns that differ between classical and quantum bits are that:

- Qubits are fragile, while classical bits are robust
- Qubits cannot be cloned or copied, while classical bits can be easily copied
- Qubits can be measured in infinitely many ways (by choosing different measurement bases), while classical bits can be measured in one way only
- Measuring a qubit disturbs the quantum state, while classical bits can be measured without altering their state

These differences in patterns are leveraged in technologies such as quantum computing and quantum key distribution.

2. Cause and effect:
Events have causes, sometimes simple, sometimes multifaceted. Deciphering causal relationships, and the mechanisms by which they are mediated, is a major activity of science and engineering.
(a) Measurement collapses the state of a qubit to one of the measurement basis states randomly. **The cause is the measurement, and the effect is state collapse**.
(b) When measuring a qubit, the probability of measuring a certain outcome depends on the choice of measurement basis. **The cause is the choice of basis, and the effect is the outcome probability.**
(c) If we change the state of a qubit to a superposition of measurement basis states, the probability of measuring outcomes will change. **The cause is the preparation of the qubit in a**

superposition state, and the effect is a change of the measurement outcome probabilities.
(d) If two qubits are entangled, their measurement outcomes will be correlated depending on the measurement bases used. **The cause is entanglement and the choice of measurement bases, and the effect is correlated measurement outcomes.**

3. Scale, proportion and quantity:
In considering phenomena, it is critical to recognize what is relevant at different size, time, and energy scales, and to recognize proportional relationships between different quantities as scales change.
(a) Quantum systems are typically much smaller than classical systems. For example, the typical size of an atom is 10^{-10} meters.
(b) Qubits are small, but two qubits can be entangled over a large distance. In quantum communication protocols like teleportation, qubits separated by many kilometers have been shown to be entangled.
(c) The standard units of mass and time are defined in relation to fundamental quantum quantities, which describe behavior at the sub-microscopic scale. The SI unit of mass (the kilogram) is defined relative to Planck's constant, and the SI unit of time (the second) is defined relative to the Cesium-133 atomic clock transition.
(d) The advantage that quantum computers can have over classical computers grows as the size and depth of the quantum system increases. One of the principal challenges of quantum computing is engineering systems containing many qubits, as sources of error such as decoherence become more difficult for larger systems.

4. Systems and models:
A system is an organized group of related objects or components; models can be used for understanding and predicting the behavior of systems.
(a) Many quantum systems can be modeled as qubits, including:
- The polarization states of photons
- The energy states of atoms
- The spin states of electrons

(b) Operations on qubits can be modeled in quantum circuits and represented as quantum gates.

5. Energy and Matter
Tracking energy and matter flows, into, out of, and within systems helps one understand their system's behavior.
(a) Over the course of a quantum computation, qubits will transition between different quantum states and superpositions. In many qubit implementations, this is realized by transitioning between different energy levels.
(b) Quantum systems exchange quantum information by exchanging energy. For example, two atoms might communicate with each other via a quantum of light energy (photon).

(c) Qubits are surrounded by an environment, including other matter and stray energy such as light. Decoherence results when the qubits interact with this environment, and is the main reason qubits are exceptionally fragile.

6. Structure and Function:
The way an object is shaped or structured determines many of its properties and functions.
(a) When considering the probability of measuring a certain outcome, we must consider both the structure of the quantum state and the structure of the quantum measurement.
(b) The structure of a quantum gate determines its function. For example, the Hadamard gate's structure allows it to create superposition states.
(d) Quantum algorithms are structured to use features like superposition and entanglement. The function of this is to obtain the correct answer to a problem with high probability. This can result in a computational advantage over classical algorithms in problems such as an unsorted search and prime factorization.
(d) Quantum key distribution protocols are structured to use multiple measurement bases. The function of this choice is to protect the secret key from eavesdroppers.

7. Stability and Change:
For both designed and natural systems, conditions that affect stability and factors that control rates of change are critical elements to consider and understand.
(a) Quantum states are fragile. The quantum states can change uncontrollably due to unwanted interaction with the environment, such as electromagnetic radiation.
(b) To reduce decoherence in a quantum computer, the system is maintained at a very low temperature. Quantum error correction techniques are being developed to protect against decoherence.
(c) Designing effective quantum gates requires an understanding of how to transform a qubit state. For example, a laser beam with the right frequency and duration can flip the state of a qubit encoded in a trapped atom.

Connections between QIS Key Concepts and NGSS

Below is a table of possible NGSS connections to QIS+Physics Key Concepts identified thus far by working group members. The majority of connections are to a few standards and in the context of information, light, electrons, and other physical systems and properties. This is an ongoing process, and in some cases the boundary for NGSS states that quantum theory is not included. We expect to update this table and generate similar tables for other standards and classes (e.g., engineering, chemistry). As the topics become more applied, there are less connections identified at this time.

QIS Topic/Concept	Paraphrased description	QIS Key Concept Section	Keywords for Connection	NGSS
1. Quantum information science	No reference			
2. Quantum State	quantum systems	2.1B	photons	HS-PS4-3
	quantum systems	2.2A	energy levels	HS-PS1-1, HS-PS1-4
	quantum systems	2.2A	forces	HS-PS1-3
	states of quantum systems	2.3A	polarization	HS-PS4-3; HS-PS1-5
	states of quantum systems	2.3B	exclusive states	HS-PS1-1, HS-PS1-2
	states of quantum systems	2.3C	energy states	HS-PS1-1, HS-PS1-2
3. Measurement	measurement, superposition	3.3B	Stern Gerlach, spin	HS-PS2-5, HS-PS2-6
	quantum measurements and state	3.4A	polarizer transmission	1-PS4-3
	randomness and Heisenberg Uncertainty Principle	3.6A	momentum	HS-PS4-3, HS-PS4-1, HS-PS2-2
	randomness and Heisenberg Uncertainty Principle	3.6C	spin of electron	HS-PS2-6

4.Qubits	quantum bit and information	4.1B	voltage and encoding	HS-PS2-5
	physical states for encoding quantum information	4.2A	perpendicular polarization	1-PS4-3
	physical states for encoding quantum information	4.2B	spin of electron	HS-PS2-6
	physical states for encoding quantum information	4.2C	energy level	HS-PS1-1, HS-PS1-4
	classical vs quantum bit	4.3A	encoding qubit-spin	HS-PS4-2
	classical vs quantum bit	4.3B	encoding qubit-polarization	HS-PS4-2
5. Entanglement	No reference			
6. Coherence	classical vs qubit (corruption)	6.2B	polarization; measurement error	HS-PS4-3; HS-PS1-5
7. Quantum Computing	comparing physical systems	7.7A	energy states	HS-PS1-1, HS-PS1-4, HS-PS2-6
8. Quantum Communication	No reference			
9. Quantum Sensors	No reference			