Quantum (Q)-Kit

Quantum Computing:

Laboratory for Secondary Level Students

Teacher Manual

WS2

WOMEN SUPPORTING
WOMEN IN THE SCIENCES

Mission Statement

The mission of this laboratory is to teach secondary level students (ages ~12-18) about quantum computing concepts through experiments related to quantum mechanics.

Contents

1. Introduction to WS2 Laboratory Kits

1.1. Information about WS2

Women Supporting Women in the Sciences (WS2), an international organization unifying and supporting graduate and professional-level women and allies in science, technology, engineering, and mathematics (STEM), was awarded an American Physical Society (APS) Innovation Fund in 2020 to form international teams to design and distribute low-cost physics and materials science lab kits to primary and secondary school students, predominantly in eastern Africa. The lab kits utilized local resources and included topics that are especially relevant to young girls in order to spur their interest in STEM subjects. From 2020-2023, over 5100 students from eastern Africa at over 40 school sites engaged with our lab kits, with 62% being girls.

WS2 was awarded their second APS Innovation Fund in 2025 to support another Lab Kit Initiative, though this time with a focus on quantum topics. For more information about WS2, please visit our website at ws2global.org.

WS2 is sponsored by the APS Innovation Fund, APS Forum on Education, Northwestern University Materials Research Science and Engineering Center, and Northwestern University Multicultural Student Affairs. WS2 is extremely grateful to the lab kit design volunteers for their hard work (John Bakayana, Celline Omondi, Alice Flarend, Elvira Khwatenge, Babra Mwimali, and Sserugo Enock) and external consultants (SciBridge and Projekt Inspire) for their advising. WS2 also thanks and acknowledges PhysicsQuest (https://www.aps.org/initiatives/physics-education/physicsquest) and Quantum Explorations Student Toolbox (QuEST) for example experiments that were used as foundation for the lab kit content.

1.2. Information about this Kit

Welcome to the exciting world of quantum science—a realm where particles can be in multiple places at once, light behaves like both a wave and a particle, and distant objects can influence each other instantly. Sounds like science fiction, but it is not!

This manual is designed to guide you through simple, hands-on experiments that bring some of the most fascinating concepts of quantum physics to life. Using everyday materials, you'll explore big ideas like superposition, interference, and entanglement—concepts that challenge our classical understanding of how the universe works.

Don't worry if these terms are new or sound complicated. Each experiment includes:

- Clear purpose statement to indicate what you are learning
- Pre-lab questions to get you thinking
- Step-by-step procedures you can follow with ease
- Simple tools you likely already have at home or in class
- Observation tables for recording your results
- Thoughtful post-experiment questions to help connect what you've seen to the mysteries of quantum science

These experiments are meant to spark curiosity, creativity, and deeper thinking. You don't need to be a physicist (yet!) to enjoy them—just bring an open mind, a sense of wonder, and a willingness to explore ideas that stretch the limits of what we think is possible. As you work through these activities, remember: even the most famous scientists started by asking simple questions and trying small experiments. Who knows what discoveries your curiosity might lead to?

1.3. Using the Guide

This manual is to be used by the teacher or facilitator of the laboratory kit, and it is similar in content to the student manual but may contain additional material, namely: Fundamental Science Concepts Covered, Practical Skills, Summary of Experiments, Teacher Pre-Lab, and Troubleshooting. These additional sections are intended to provide the teacher with the background and foundation critical for successfully implementing this laboratory kit in the classroom. It is recommended that the teachers of this laboratory kit go through the guide from beginning to end to familiarize themselves with the content prior to teaching the laboratory kit to students. Questions about the content can be directed at any time to ws2global.org@gmail.com, using the subject line "Question about Lab Kit Content".

<u>IMPORTANT NOTES:</u>

- This laboratory kit is intended for use with secondary-level students (ages ~12-18), but depending on the specific students' educational background, the content may need to be modified by the teacher to be made simpler or more complex. The teacher is encouraged to also cover the content at the pace that works best for the students; some younger students may need more time and attention from the teacher and/or facilitator to go through the questions and experiments, while older students may be more independent and require less attention from the teacher and/or facilitator. Thus, the content covered, depth of coverage, and pacing are left to the teacher's and/or facilitator's discretion.

- The content in this lab kit manual may not fit into the specific curriculum of the school in which it is being taught. It is up to the facilitator(s) and teacher(s) whether they would like to introduce new content or skip certain sections that are not applicable to their classrooms.
- In certain areas, modifications to the supply list may need to be made depending on the availability of the supplies in the specific area in which the lab is being taught. We have attempted to list some alternatives in the supply list, but we understand this list of alternatives is not exhaustive.
- In the experiments, the students are split into groups of three to four. If supplies allow, students may instead be split into groups of two.

1.4. Key Vocabulary

- Bit (classical): the 0s and 1s that traditional classical computers use
- Qubit (quantum bit): fundamental unit of quantum information in quantum computing that can exist as 0 or 1 simultaneously
- Measurement: the process of collapsing the superposition state of a qubit into a (0/1) definite state
- Superposition: a system (like a qubit) existing in multiple states at once until measured
- Entanglement: the linking of states in objects no matter how far apart they are
- Quantum gate: a device that changes the quantum state of a qubit
- Quantum cryptography: a method of secure communication that encodes messages in qubits

1.5. Key Questions

- What is a qubit, and how does it differ from a classical bit?
  - *Answer: The fundamental differences between classical bits and qubits lie in their behavior, capabilities, and underlying physics.*
    - *A classical bit exists in a definitive state of either 0 or 1, much like a traditional light switch that's either on or off. In stark contrast, a qubit operates in the quantum realm, where it can simultaneously embody both 0 and 1 states through superposition – a core quantum property that has no classical equivalent.*

        - *While classical systems cannot achieve superposition, this phenomenon allows qubits to process information in parallel across multiple states. Entanglement, another quantum exclusive, enables qubits to form interconnected states that remain correlated even when separated by vast distances, creating a powerful computational resource absent in classical computing.*
        - *The information capacity scales dramatically differently between the two systems: classical bits store data in discrete 1-bit units, whereas qubits leverage quantum mechanics to achieve exponential scaling potential. This capacity for parallel processing and quantum correlation forms the foundation of quantum computing's revolutionary power.*

- What is superposition?
    - Answer: *Superposition is not analogous to a flipping coin (which lands as heads or tails). Instead, it represents a quantum system existing in multiple states simultaneously until measured. For example, an electron's spin isn't merely "unknown" but is genuinely in both spin-up and spin-down states at once.*

- How does a quantum computer differ from a classical computer that uses binary 0s and 1s?
    - Answer: *Classical computers process binary data sequentially. Quantum computers use superposition to explore multiple solutions at once and entanglement to correlate qubits' states. For example, while a 2-bit classical system can represent four states (00, 01, 10, 11) one at a time, two qubits in superposition can represent all four simultaneously.*

1.6. Purpose

The purpose of this lab kit is to learn about quantum computing through experiments and activities. Students will learn about the difference between classical bits and qubits and the concepts of superposition and entanglement. Students will also engage in activities that teach them about quantum cryptography and quantum computing through games and analogies.

1.7. Fundamental Science Concepts Covered

This laboratory kit introduces the topics of quantum computing and quantum cryptography, relevant to numerous fields including Physics and Computing, to middle and high school/secondary-level students. Specifically, the lab kit encourages students to think about the principles behind quantum computing and how it differs from classical computing by exploring key concepts like superposition, wave interference, and entanglement through games and activities. Students will come away with the following key takeaways: (1) superposition means something can exist in multiple states at once prior to measurement; (2) polarized photons passed along a quantum channel form the basis for creating a secure key in certain quantum cryptography protocols; (3) quantum gates utilize superposition and entanglement to manipulate qubit state and phase in ways not accessible by classical computing gates.

1.8. Practical Skills

- Students will understand how classical computers are different from quantum computers.
- Students will gain experience with probability and randomness in the context of statistics.
- Students will utilize logic and rules to predict outcomes.

2. Background on Main Topics

2.1. Quantum bits (Qubits) and Quantum Computers

Quantum computing, which is computing that utilizes quantum mechanical properties, is sought after because it can perform computations that are impossible for classical computers. How does a traditional computer work? Traditional computers process information using fundamental units of data called classical bits (either 0s or 1s). These bits are manipulated through logic operations which allow the computer to complete simple and complex tasks. How is a quantum computer different? Unlike classical bits that represent 0 or 1, quantum bits, or qubits, in quantum computers can exist in superposition, which is a state in which the bit exists both as 0 and 1 simultaneously (see Figure 1). To collapse a superposition state, the qubit is measured, which means the qubit is no longer 0 and 1 simultaneously, but instead is either a definite 0 or 1.

What is another way to think about superposition? Imagine a light switch. It can be either ON (1) or OFF (0). This is like a traditional computer bit. Now, imagine a special light switch that can be ON, OFF, or both at the same time! That would be like a qubit. This "both at once" superposition ability is what gives quantum computers their power. While traditional computers can only process traditional bits (0 or 1), quantum computers can process 0, 1, or both, which means they can explore multiple possibilities at once.

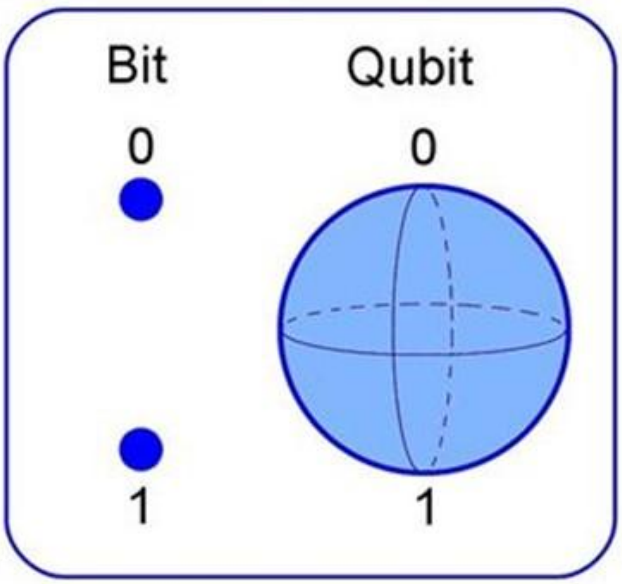


Figure 1. Illustration of classical bit (left) and qubit (right). The classical bit can either be a 0 or 1, and the qubit can exist in superposition as both a 0 and 1 simultaneously. This Photo by Unknown Author is licensed under CC BY

Like traditional computers, quantum computers follow instruction sets called algorithms that employ logic gates to manipulate bits in a specific order. Instead of using classical gates (like "AND", "OR"), quantum computers use quantum logic gates, which are devices that manipulate qubits using quantum mechanics. For example, a Hadamard gate puts a qubit into a superposition state (both 0 and 1).

What are other quantum mechanics phenomena that quantum computers utilize? Entanglement, which is the linking of states (like qubits) no matter how far apart they are, is used in quantum computers to create powerful quantum algorithms and communication methods. If you think back to the light switch analogy from superposition, now imagine two entangled light switches. If you flip one, the other instantly flips too, even if they are far apart! That is one spooky connection!

How could quantum computers be useful in our lives? Because quantum computers can explore multiple possibilities at once with qubits, they can work faster and more efficiently than traditional computers. This could be extremely useful in a variety of fields including drug discovery, materials science, and artificial intelligence. Quantum computers could also be used in cryptography, which is the way information is secured from unauthorized access. Classical cryptography uses math to scramble messages. Quantum cryptography uses qubits and quantum mechanics to create unbreakable codes. If someone tries to eavesdrop on a quantum message, the spy will disturb the qubits, and the sender will know someone is listening!

3. Summary of Experiments

This lab kit consists of one experiment, two activities, one optional supplemental computer programming procedure, and one design challenge to understand concepts related to quantum computing. This investigation will begin by providing relevant quantum computing background, before demonstrating phenomena that emerge in these systems. If your school does not have access to computers, the Supplemental Activity can be skipped. The goals of the experiments and design challenge are the following:

Part I: To demonstrate superposition with the hiding of a flipped coin and collapse of superposition with its measurement

Part II: To understand the BB84 quantum cryptography protocol using candies and color to represent photons and polarization

Part III: To demonstrate quantum computing gates, which include superposition and entanglement of qubits, using a game

Design Challenge: To design a challenge that changes a qubit state and phase using quantum computing gates

3.1. Supplies List

- Coins (metal with two distinct sides)
- Opaque cups
- Paper

- Wrapped candies (or small pieces of paper)
- Buckets or jars
- Markers
- Colored tape (red and green) (2 other colors may also be used)
- Save Schrödinger's Cat game pieces for each group:
  - 8 blue cat/red cat tokens to act as qubits
  - 8 yellow cat/green cat tokens to act as qubits
  - 2 X gates
  - 2 Y gates
  - 2 X gates
  - 2 S gates
  - 2 H gates
  - 1 CNOT gate
  - 1 qubit gate phase change table
  - 1 qubit Interference table
- Scissors
- Clear tape

3.2. Safety Information

Before the students begin the laboratory, please take into consideration the following safety concerns:

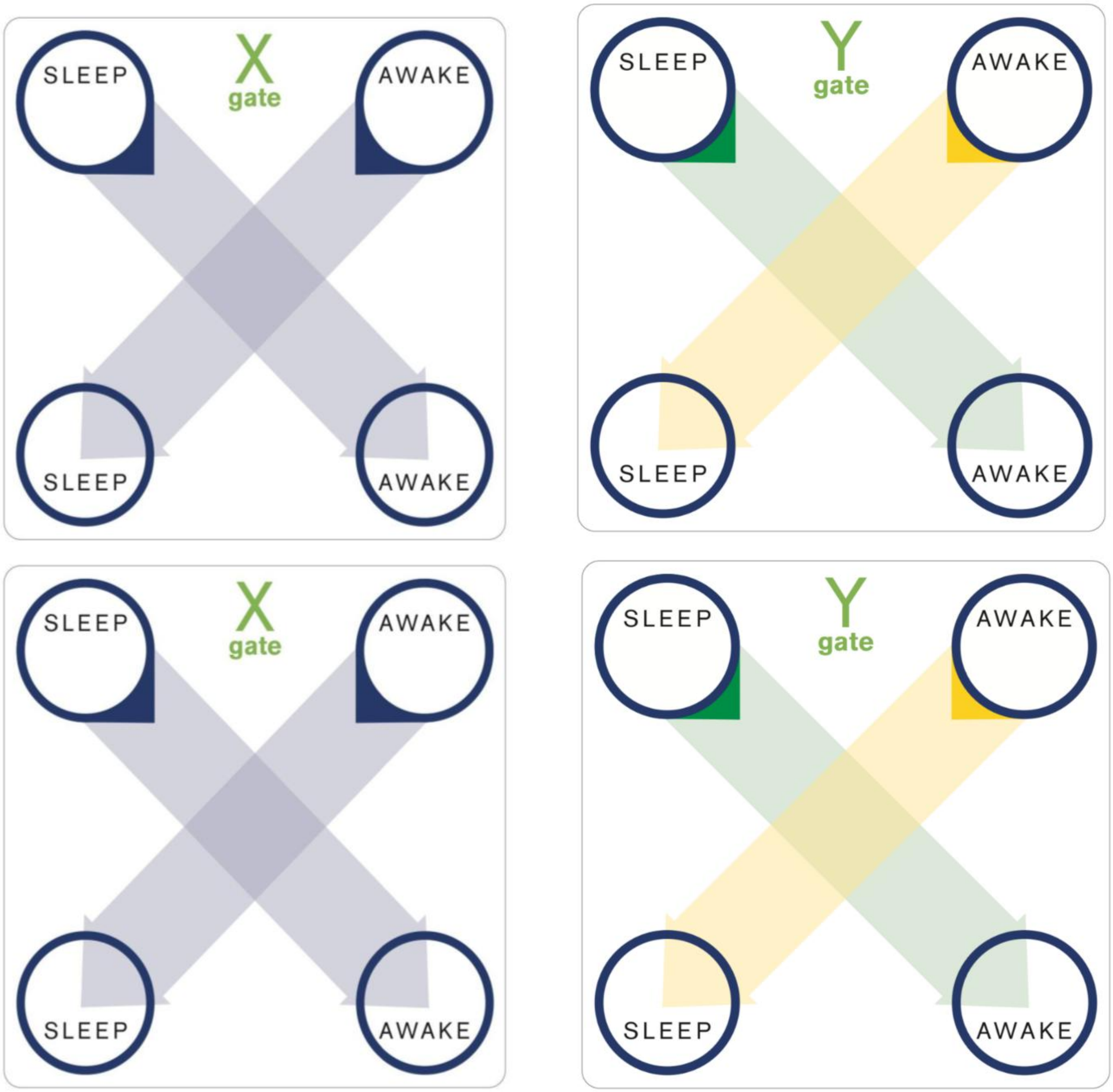
- This lab kit has no major safety concerns associated with it.

3.3. Teacher Pre-Lab

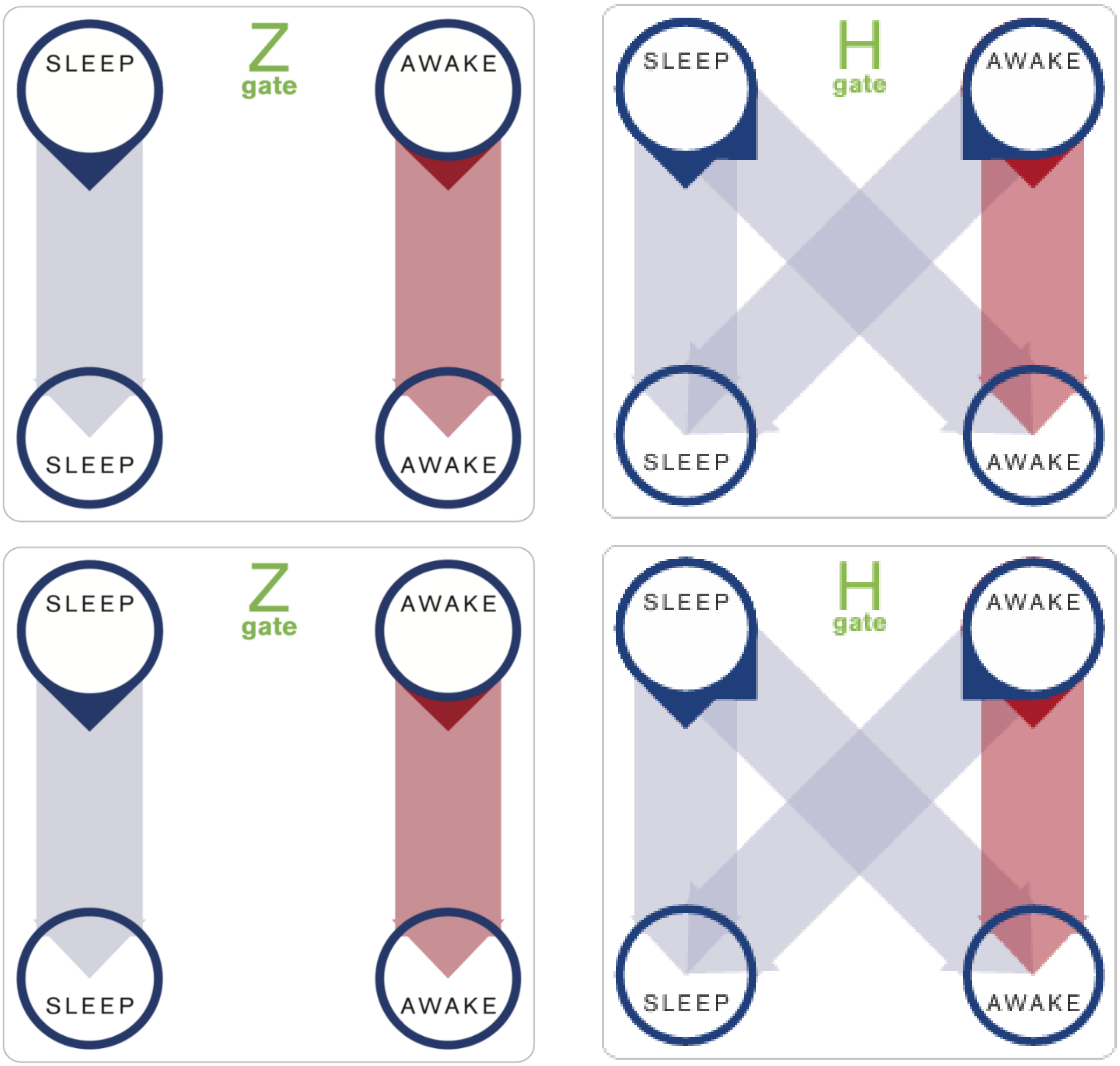
Teachers can organize the supplies for the experiments and activities ahead of time. For each student or each group of 2-4 students, the materials needed are: 1 coin (with two distinct sides), 1 opaque cup, 40 wrapped candies (or 40 pieces of paper), 2 buckets or jars, the game pieces for Part III (see below), and a pen or pencil. There should be colored tape and markers that the classroom can share. If doing the optional supplemental activity, each group should have access to a computer with Python installed, or the teacher can project the program to the students on a screen or board.

Teachers can watch a YouTube demonstration of the game in Part III at https://www.youtube.com/watch?v=1OEqjGWOUhM. Teachers should print and prepare the following for each group for Part III:

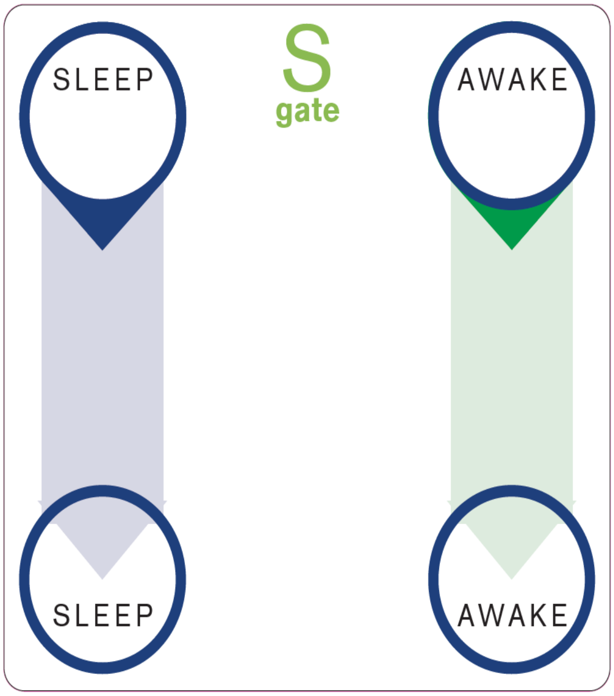
These cats should be cut into 16 tokens (red/blue and yellow/green) and then folded and taped such that one side shows red and the other side shows blue for 8 of the tokens and one side shows yellow and the other side shows green for the other 8 tokens.

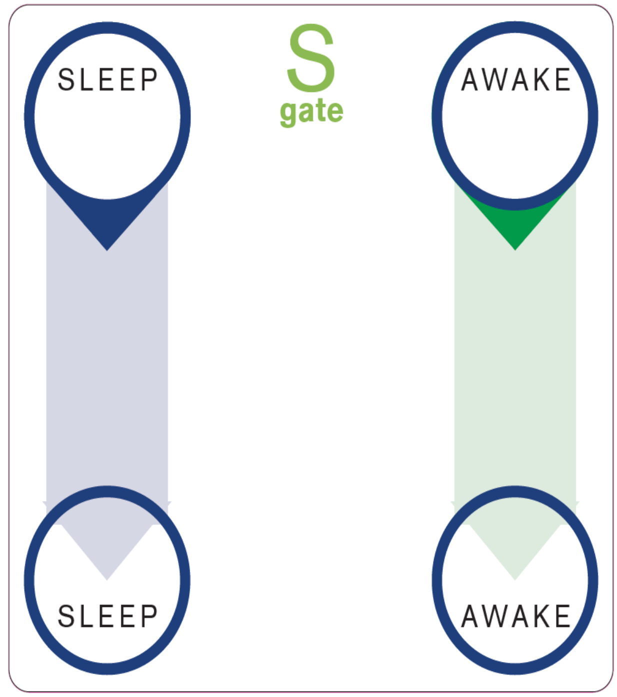


These can be cut into 4 distinct gates (2 X and 2 Y).



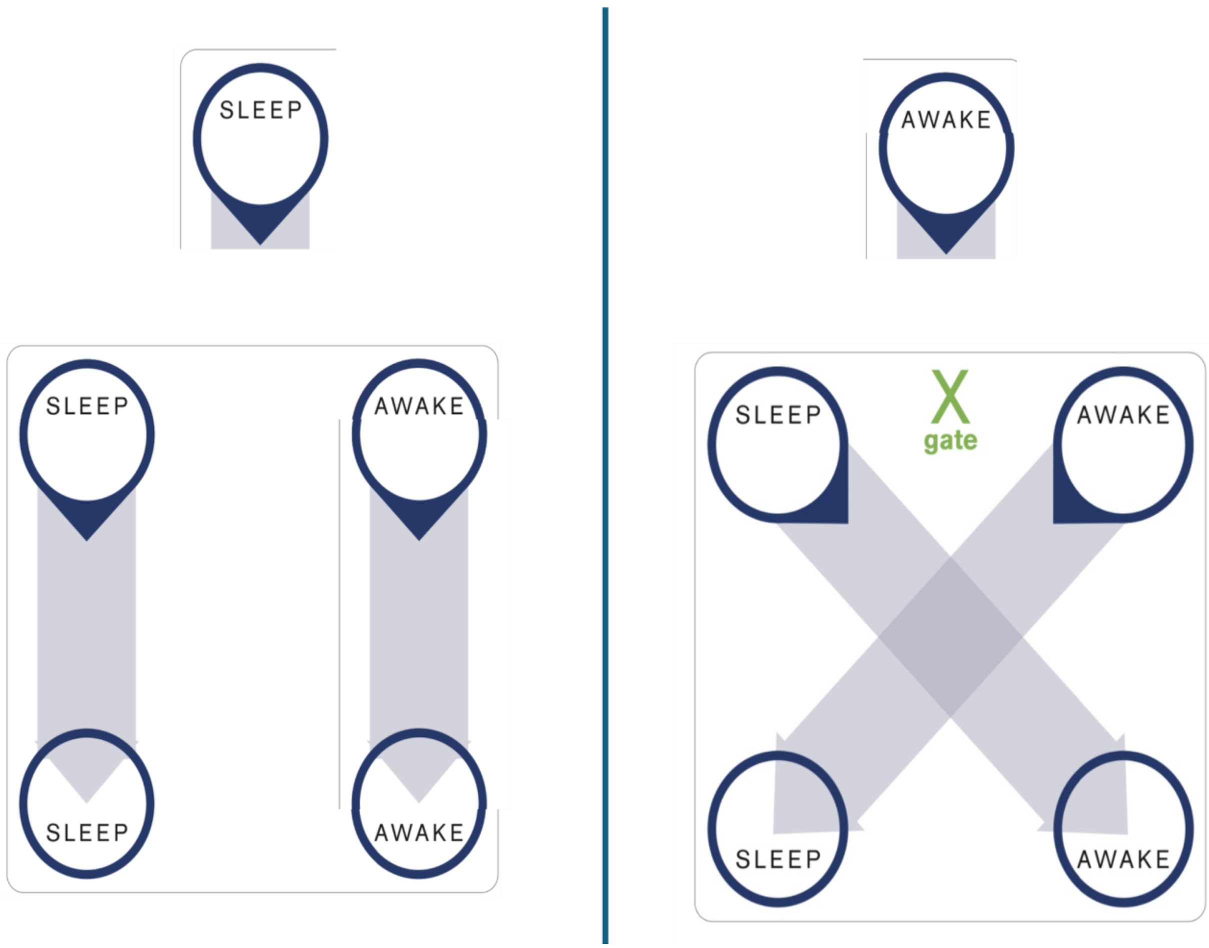
These can be cut into 4 distinct gates (2 Z and 2 H).

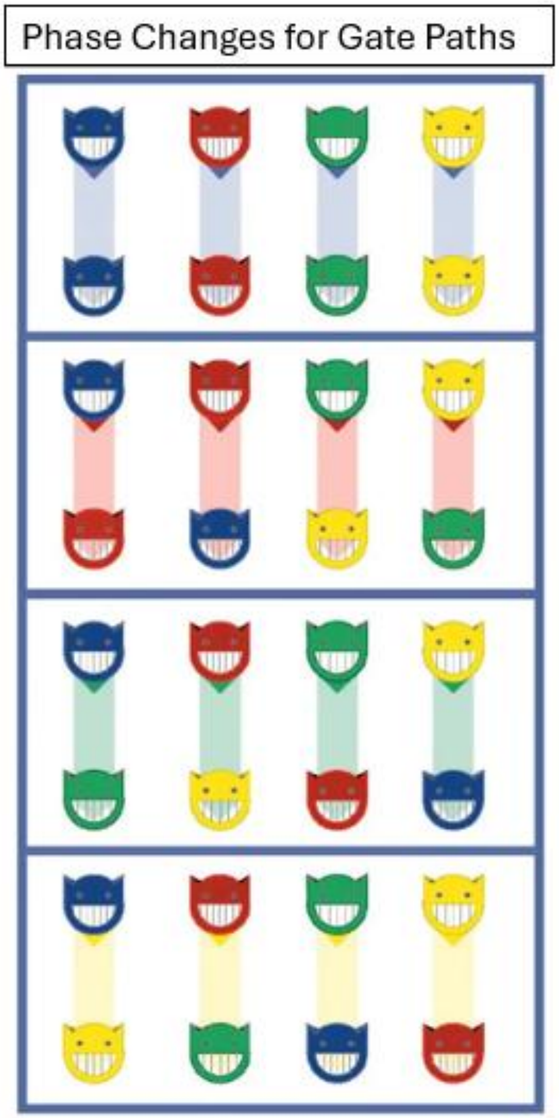


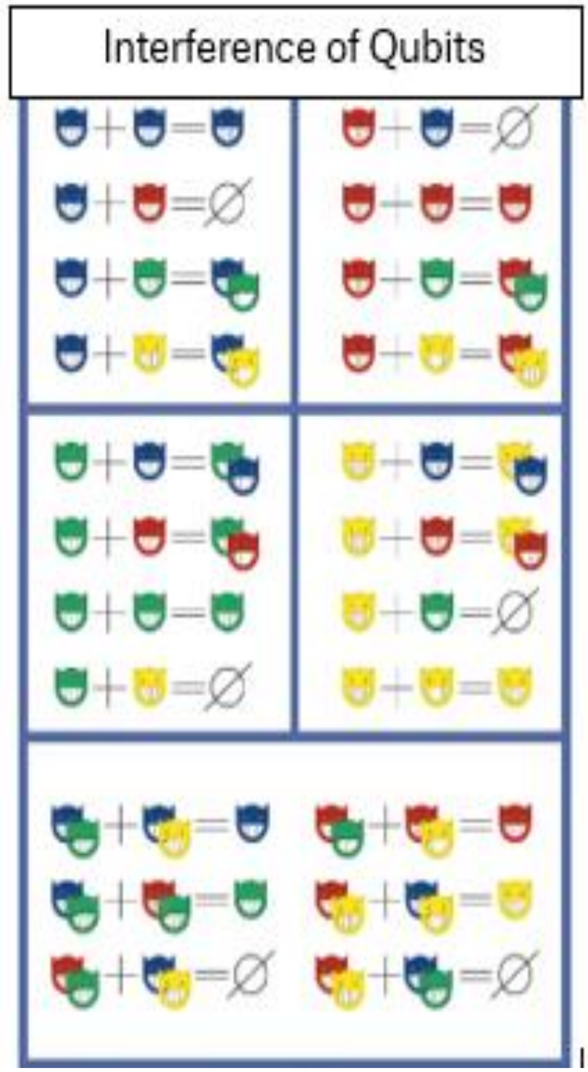


These can be cut into 2 distinct gates (2 S).

CNOT


SLEEP
AWAKE
SLEEP
AWAKE
SLEEP
AWAKE
SLEEP
X gate
AWAKE
SLEEP
AWAKE


Phase Changes for Gate Paths


Interference of Qubits

4. Experiments

<u>Note for teachers:</u>

Encourage open discussion and questions from the class when introducing the experiments.

4.1. Part I. Quantum Coin Flip

4.1.1. *<u>Pre-Experiment Questions</u>*

1. What does it mean for a quantum system to be in a superposition state? How does this differ from classical systems?
   a. *<u>Answer:</u> Superposition means a quantum system (like a particle) exists in a combination of all possible states simultaneously, described by a probability wave. For example, an electron in an atom isn't at a single location but exists as a "cloud" of probabilities, represented mathematically by overlapping waves. This isn't just uncertainty-it's a fundamental coexistence of states until measured.*

2. Can you know the exact state of a quantum system without measuring it? Why or why not?
   a. *<u>Answer:</u> Knowing the state without measurement is impossible. Before measurement, the system's state is a superposition of probabilities (e.g., an electron's position or a qubit's 0/1 state). Measurement forces the system to "choose" a definite state, destroying the superposition*

4.1.2. *<u>Materials</u>*

- Coins (metal with two distinct sides)
- Opaque cups

4.1.3. *<u>Procedure (work in groups of 2-4)</u>*

1. Flip a coin onto a table or other hard surface and place the cup over it without revealing if it is heads or tails.
2. Predict whether the coin is heads or tails.

3. Measure the coin by lifting the cup and record the results.
4. Repeat 20 times.

4.1.4. *Results*

Coin flip	Heads or Tails?
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
11	
12	
13	
14	
15	
16	
17	
18	
19	
20	

4.1.5. *Post-Experiment Questions*

1. What was the percentage of times you measured heads? Tails? How did this vary in your classroom?
    a. *Answer: This will vary. Students should calculate percentages by dividing the number of heads by the total number of flips and multiplying by 100.*

2. How do these percentages relate to the expected probability of heads versus tails?
    a. *Answer: The expected probability of heads is 50%.*

3. What could you do to get your measured percentages to approach the expected probability of heads versus tails?
    a. <u>*Answer:*</u> *To get the measured percentages to approach the expected probability, you could increase the number of flips.*

4. If we consider the coin to represent a qubit, what state is the qubit in when it is under the cup prior to measurement? What about after measurement?
    a. <u>*Answer:*</u> *The qubit is in a state of superposition when it is under the cup prior to measurement (both heads and tails). After measurement, the qubit is either heads or tails.*

5. How do we collapse the superposition state of the coin?
    a. <u>*Answer:*</u> *We "measure" the coin by lifting up the cup.*

4.2. Part II. Quantum Cryptography

4.2.1. *Additional Background*

Quantum key distribution (QKD) is a way to exchange cryptographic codes (keys) securely using quantum physics. Here, light is used to pass information between two parties. Imagine that Alice wants to send Bob a message, but they do not want anyone else to read it. Alice sends Bob a secret code (a key) using tiny particles of light called photons. Here is the quantum twist: if someone tries to listen in (like Eve), the person will disturb the photons, and Alice and Bob will know. It is like having a secret alarm system for your message. Think of information you want to keep safe – phone messages, bank account passwords, and PINs. These are all areas in which quantum cryptography could be helpful!

There are many ways quantum cryptography can protect our information, but what about situations in which quantum computers are being used to try to steal our information? In this case, we use quantum physics to combat these attacks. Specifically, post-quantum cryptography (PQC) is a sub-field of quantum cryptography that develops algorithms to protect against quantum computers (see Figure 2), As quantum computers get more powerful, the ways we protect our data now might not be enough. PQC encryption is designed to be super resistant to attacks, even from quantum computers.

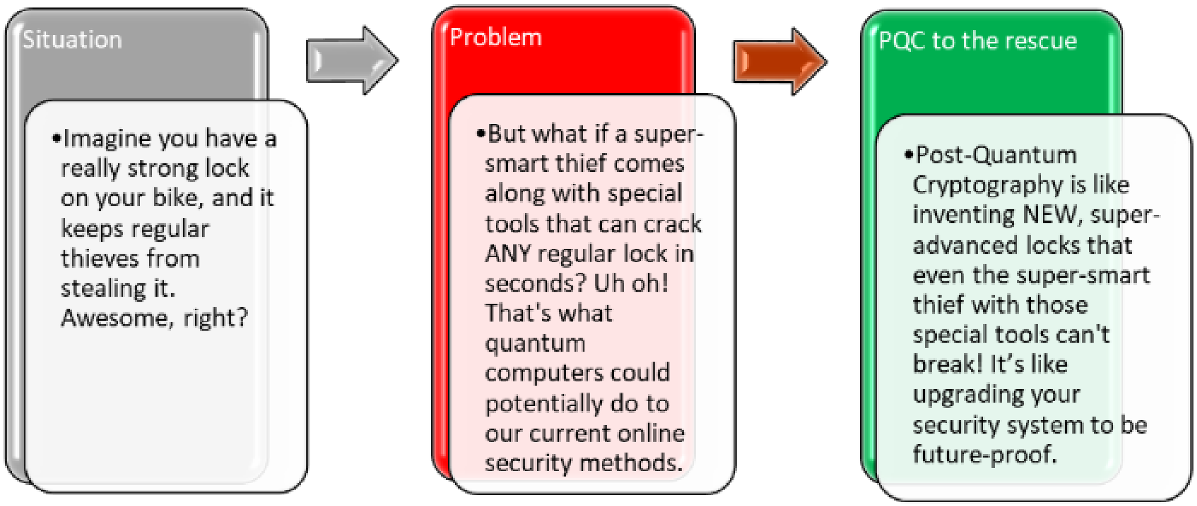


Figure 2. How can we think about post-quantum cryptography? Consider the analogy in which you have a bike (left) but there is a thief (middle) and PQC serves as a special lock to protect your bike (right).

In this activity, we are going to simulate a quantum cryptography protocol – the BB84 protocol – to send a message between two people (Alice and Bob) that will create a secret key they can use in the future to decode messages. In the real-life BB84 protocol, photons with different polarizations are sent across a communication channel using filters. Think of it like developing a secret handshake with light! Polarization refers to the orientation of the photon's oscillations – think of it like the direction a photon is pointing its electric field. Filters are like tiny gates that only let photons oscillating in a certain direction pass through. The receiver of the message uses similar polarization filters to guess in which direction the sender sent the photons. After sending a long string of photons, Alice and Bob can publicly share their filters to decide which bits to keep (when the filters match) and which to discard (when the filters do not match) for their secret key. An interesting feature of this protocol is that it has eavesdropping detection, as any effort to spy on the photons changes them. So, if Alice and Bob measure an error rate (the rate at which their filters do not match) that is higher than random, they can guess their communication is being eavesdropped and they do not use their communication to form their shared secret key.

How can we simulate the BB84 protocol? We will need something to represent the photons and how we filter them. Here we will use two types of wrapped candies: one type will have 0s or 1s written on them and one type will have red or green markings. Alice will select one of each randomly to assign her photon bit and color and record this information. Think of these two descriptors (bit and color) together as an analogy for the photon's polarization. Alice will then pass the bit candy to Bob, and Bob will randomly select a color candy to "view" the bit. Bob will record the bit and color information. This process will be repeated several times to represent a string of photons being passed through the quantum channel. Then, Alice and Bob will publicly compare their color information for the photons. If the colors match, they keep bits; otherwise, they discard the bits.

4.2.2. *Pre-Activity Questions*

1. What is a polarization filter? How is this used in the BB84 protocol to encode and decode photons?
    a. *Answer:* *Polarization filters (like sunglasses for light) only let through photons aligned with their orientation. In BB84, Alice randomly uses a filter to polarize photons, and Bob randomly picks a filter to measure the photons. If Bob's filter matches Alice's, Bob has the correct bit. If not, the result is random.*

2. What information will you be recording about your "photons" in this activity? Why is this information chosen randomly?
    a. *Answer:* *You will record the "photon" bit and polarization (color) in this activity. The polarization filter (color) is chosen randomly to ensure the key remains secret (unless an eavesdropper risks being caught).*

4.2.3. *Materials*

- Wrapped candies (or small pieces of paper) (40 pieces total per group)
- Buckets or jars (2 per group)
- Markers
- Colored tape (red and green) (2 other colors may also be used)

4.2.4. *Procedure (work in groups of 2-4)*

1. Select one person in your group to be Alice and one to be Bob. The other group members can act as Alice's and Bob's assistants and record the information about the "photons" that are passed during this activity.
2. Write 0 on 10 candies (or pieces of paper) and 1 on 10 candies (or pieces of paper) and place them in one jar. Shake them to ensure they are well mixed.

3. Put red tape on 10 candies (or pieces of paper) and green tape on 10 candies (or pieces of paper) and place them in a second jar. Shake them to ensure they are well mixed.
4. Alice selects one candy from each jar randomly and records the bit and color information.
5. Alice passes the bit candy only to Bob.
6. Bob selects one candy from the jar with different colors of candies and records the bit (from Alice) and color (from the jar) information.
7. Repeat steps 4-6 at least 5 times and up to 10 times.
8. Alice and Bob publicly share the color information for the "photons". If the colors match, they keep the information; otherwise, they discard the information.
9. Change roles in the group and repeat steps 4-8.

4.2.5. *Results*

Alice's results

Photon	Bit	Color	Keep or Discard?
1			
2			
3			
4			
5			
6			
7			
8			
9			
10			

Bob's results

Photon	Bit	Color	Keep or Discard?
1			
2			
3			
4			
5			
6			
7			
8			

9			
10			

4.2.6. *Post-Activity Questions*

1. Describe your roles as Alice and Bob.
    a. *Answer: Alice encodes random bits as polarized photons and sends them to Bob. Bob measures photons using randomly chosen bases, then reconciles results with Alice. If there is an eavesdropper (like Eve), this person attempts to intercept and measure photons, inevitably introducing errors that expose her presence.*

2. What did the candies and information on the candies represent in this activity?
    a. *Answer: The candies represent bits (0 or 1) and the colors (red or green) represent the photon polarization.*

3. What was your error rate (what percentage of the time did you have to discard your photons)? How does this relate to the random chance you would have to discard your photons?
    a. *Answer: The error rate will vary for each group. The random chance that Bob will have to discard his photon is 50%.*

4. How could error rate be used to determine if someone is eavesdropping on your communication in the BB84 protocol?
    a. *Answer: If the error rate is higher than random chance, there is a possibility that someone is eavesdropping on the communication.*

4.3. Part III. Quantum Computer Gates

This game in this section is based on the Save Schrödinger's Cat activity from PhysicsQuest (American Physical Society).

4.3.1. *Additional Background*

Instructions the computers use for achieving tasks are called logic circuits, and the building blocks of these circuits are called gates. The result of executing any such circuit in a classical computer will always have just one of two states: False or True. We could call these states anything we want, though, like Sleep or Awake. A computer programmer's job is to build circuits that cause the states to change in ways that solve a problem.

The game Save Schrödinger's Cat will teach you about how the logic of quantum mechanical systems is fundamentally different from classical mechanics. The first key difference is the use of the phase of a qubit, which is a wave-like property that describes the timing of the wave relative to a reference position. Classical computer gates do not affect the phase of the bit, but many quantum gates do. This means there are additional tools to solve problems using quantum computers.

The second key difference comes from the interference of bits, which if we consider qubits as a wave-like object is basically wave interference. Wave interference is the addition of two or more waves. Interference is affected by the phase of the wave representing the qubit. A wave may begin at the height of zero or it may begin at its maximum height, or it may begin somewhere in between. It can even be negative! This means that when two waves are added together, the result can vary. For example, the maximum heights of the waves may align so the addition gives a larger height. This is called constructive interference. Or the resulting height may be zero if the waves are the same height, but one begins in the positive and the other in the negative. This is called destructive interference. Figure 3 shows examples of wave interference.

Wave interference plays an important role in the quantum gate called the Hadamard gate. As discussed earlier, this gate puts the qubit in a state of superposition, meaning the bit is in two or more states at once. This can be thought of as being able to run logic gates on the two states at the same time instead of one at a time in classical computers. Superposition is a property that only exists in a quantum state and,

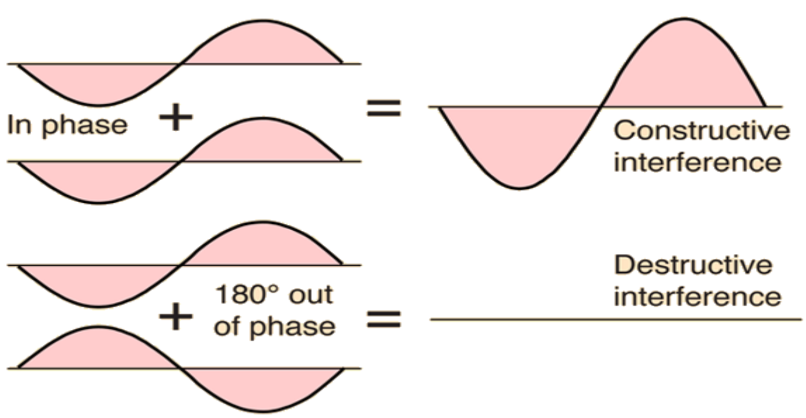


Figure 3. Constructive interference is when two waves add together to give a larger total height (top). Destructive interference is when two waves out of phase add together to give a wave with zero height (bottom). In quantum computing, quantum gates can impact the phase of the qubit. This is unique to quantum computing, as classical gates do not impact the phase of the bit. This Photo by Unknown Author is licensed under CC BY-NC.

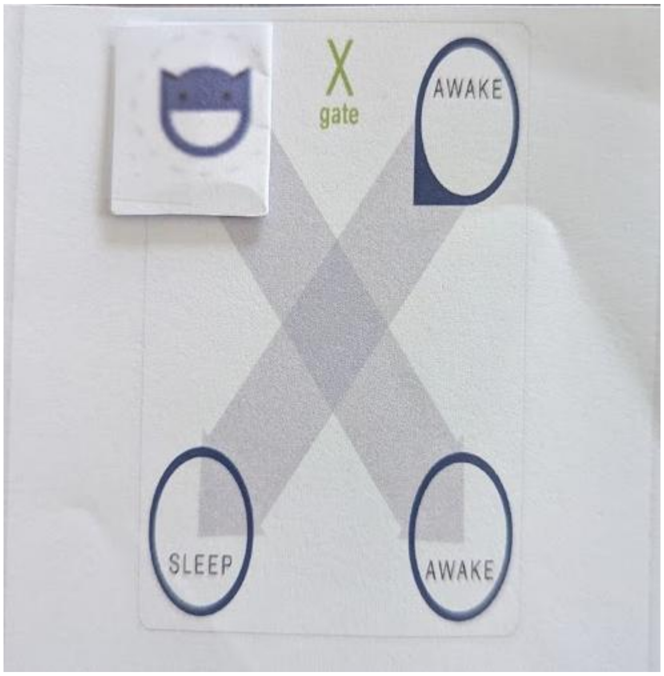
therefore, cannot be used in classical computers. For the purpose of this game, the zero (0) state is the cat being asleep and the one (1) state is the cat being awake. The phases of the qubit are represented as colors.

4.3.2. *Materials (for each group)*

- 8 blue cat/red cat tokens to act as qubits
- 8 yellow cat/green cat tokens to act as qubits
- 2 X gates
- 2 Y gates
- 2 X gates
- 2 S gates
- 2 H gates
- 1 CNOT gate
- 1 qubit gate phase change table
- 1 qubit Interference table

4.3.3. *Procedure & Analysis (work in groups of 2-4)*

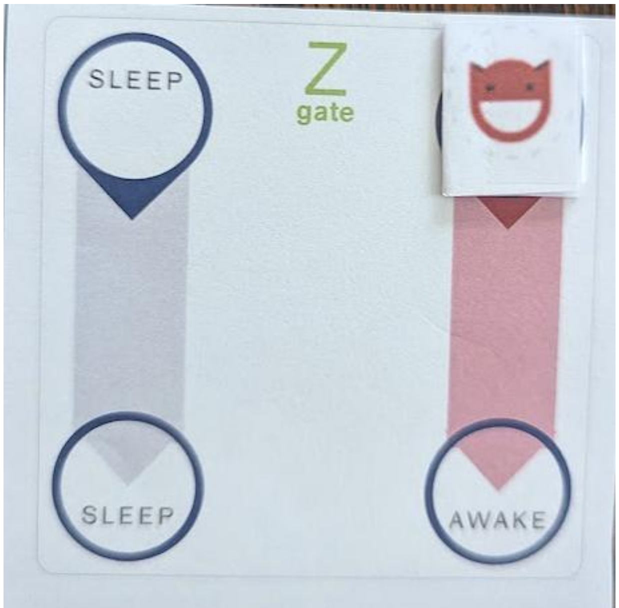
1. Lay out your QubitCats according to color.
    a. *Note to teacher: It might be worthwhile helping the students become familiar with the colors of the cats which are the phases of the waves they represent, as opposed to the color of the paths which can change those phases. You can ask students to look at the Phase Change table and ask questions like "How can a red cat be turned yellow?"(ANSWER = take a green path) or " How can a green cat remain green?" (ANSWER= take a blue path).*
2. Place an X gate where everyone can see it. Your first challenge is to wake up a blue cat. Place a blue cat token on the Sleep circle.



3. Notice that the blue path crosses over to the Awake side of the gate. Use your QubitCat phase change table to determine if a blue cat traveling on a blue path changes color. If the color does not change, place a blue cat on the Awake circle. If it does, then place the correct color of cat on the circle. Record this result in your table.
    a. *Note to teacher:* *Students should notice the blue path does not change the color (phase) of the cat. A blue asleep cat becomes a blue awake cat.*
4. Repeat with the red, green, and yellow cats being in the initial state of Sleep. Record your results for the other colors.
    a. Can you use an X gate to wake up any colored cat?
        i. *Answer:* *Yes. Cats remain the same color and become awake.*

5. Your next challenge is to change an awake red cat into an awake blue cat.
    a. Can you use an X gate to do this?
        i. *Answer:* *No, the X gate does not change the color (phase) of the cat.*

6. We will try other gates. Lay out the Z gate and place a red cat token on the Awake circle. Use your QubitCat phase change table to determine the effect of the red path on a red awake cat.

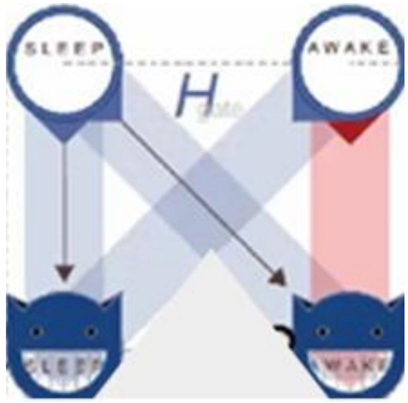


a. Did you change the phase of the red awake cat to a blue cat? Note this in your results table.
   i. _Answer:_ *Yes, the awake red cat becomes an awake blue cat.*

b. Can you change an awake green cat into an awake yellow cat using the Z gate? Note this in your results table.
   i. _Answer:_ *Yes, the awake green cat becomes an awake yellow cat. The state of the cat is not changed, but its color (phase) is.*

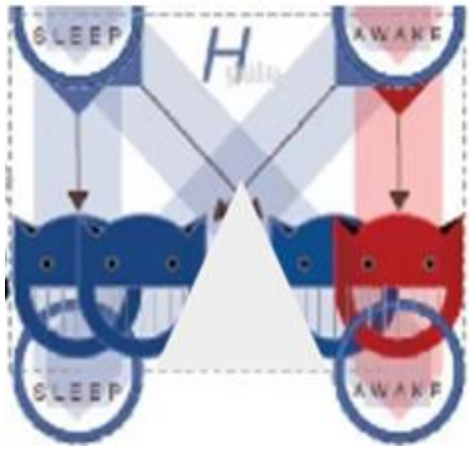
7. There are two more gates to work with, called the Y gate and the S gate. Try them out to see which one will change an asleep red cat into an awake yellow cat. Note the results in your table.
   a. _Note to teacher_ *The asleep red cat turns into an awake yellow cat with a Y gate. The asleep red is unchanged in a S gate.*

8. There are more to quantum gates than just these four you have tested. Quantum computers can also place qubits into superposition. This is called preparing the state. Quantum computers use Hadamard (H) gates for this. Lay out your H gate and trace the two paths from Sleep and the two paths from Awake. Look for phase changes in any of the paths. Start a new challenge by placing a single blue cat on the Sleep circle in an H gate. This will result in a cat in two different states (Sleep and Awake), as shown in the picture below. Note that there is still only a single cat, but it is in a state of superposition (both Sleep and Awake), which you learned about in your earlier experiment with the coins.



9. Now, when we apply another gate, we have both states to work with. Use the superposition blue cat (two tokens) as the input for a Z gate. This means you "apply" a Z gate and move the asleep blue cat from the H gate to the Z gate Sleep circle and also the awake blue cat from the H gate to the Z gate Awake circle. Be sure to check for phase changes as you apply the Z gate.
    a. <u>Note to teacher</u> *Asleep blue cat on Z gate will remain asleep blue cat. Awake blue cat will change to awake red cat.*
    b. 

10. To obtain a final result, we must make a measurement by applying a second Hadamard (H) gate. Unlike the first time you used the H gate, now there are tokens in both the awake and asleep states. This will result in four cat tokens on the bottom of the second Hadamard (H) gate, with (two on the Sleep circle and two on the Awake circle). There is an example of what this looks like below (though this is not for this challenge).



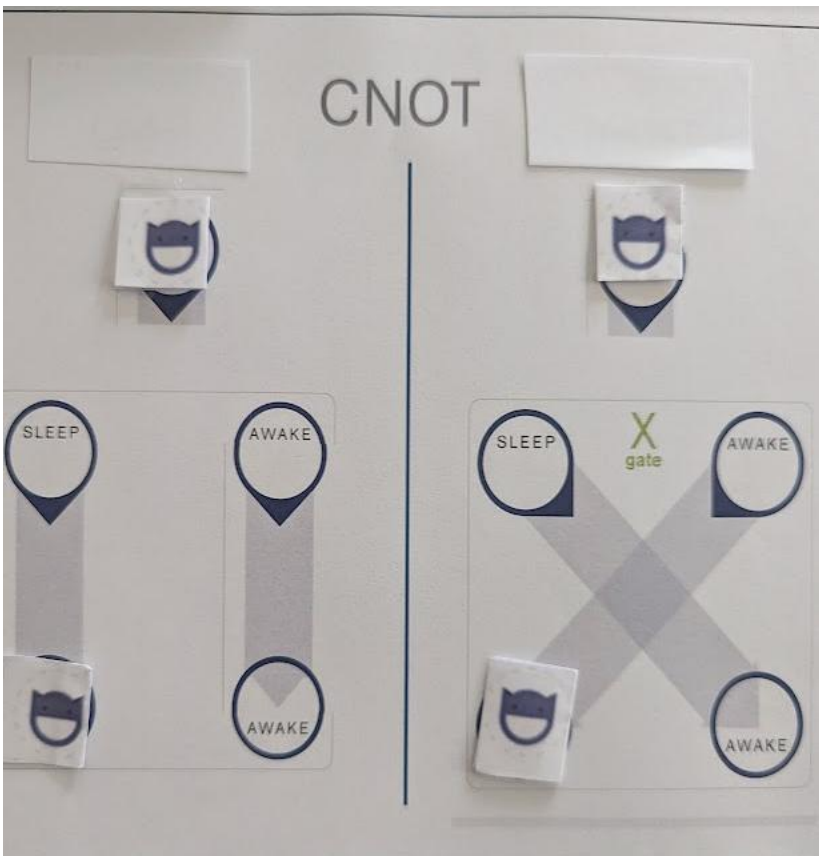
11. When two cat tokens occupy the same space, they interfere with each other and may cancel out. When used properly, there will be only one cat left because the other pair will interfere to cancel each other out. Use your QubitCat interference table to determine the final result of your cat.
    a. Did you wake your blue cat up? Record the result in the table.
        i. *Answer:* *The asleep blue cat stays blue and is now in both Sleep and Awake places. The awake red cat becomes both an asleep red and awake blue cat. Looking at the interference table, red + blue = zero, but blue + blue = blue. Therefore, there is now a single awake blue cat.*

ii. 

12. Here is another challenge: start with a red sleeping cat. Apply an H gate and then a Y gate. Finish by taking a measurement by applying the second H gate.
    a. Do you have an awake cat?
        i. *<u>Answer:</u> Yes, there is an awake green cat. Now, the interference gives green + green = green, and yellow + green = zero.*

13. There is one more very special gate unique to quantum computing, called a CNOT gate. The "C" stands for controlled, and two qubits are needed. The qubit at the top of the gate is the control bit and the target qubit is in the bottom part of the gate. If the control qubit is in the Sleep state, the target qubit follows the path on the left starting in the same state as the control qubit (here, Sleep). Examine the path to see if the target qubit has a change of state. If, instead, the

control qubit is in the Awake state, the path on the right is followed (again, the target qubit follows the path on the right in the same state as the control qubit (here, Sleep). Examine that path and note if the state or phase of the target qubit is changed. As you can see, the state of the target qubit is dependent on the state of the control qubit. This is an example of entanglement. Entanglement is a property of the two-qubit system and is a unique quantum phenomenon.

14. Fill in your result table to show the state of an awake blue cat with an awake control cat in the CNOT gate. Repeat with an asleep blue cat and an asleep control cat.
    a. *Note to teacher:* *The Awake control bit causes the awake blue cat to change to asleep blue cat. The Sleep control bit causes the asleep blue cat to remain the same.*
    b. 

4.3.4. *Results*

	Starting		Ending	
Gate	Color (phase)	State (bit)	Color (phase)	State (bit)
X	Blue	Sleep	*Blue*	*Awake*
X	Red	Sleep	*Red*	*Awake*

X	Green	Sleep	*Green*	*Awake*
X	Yellow	Sleep	*Yellow*	*Awake*
Z	Red	Awake	*Blue `*	*Awake*
Z	Green	Awake	*Yellow*	*Awake*
Y	Red	Sleep	*Yellow*	*Awake*
S	Red	Sleep	*Red*	*Sleep*
HZH	Blue	Sleep	*Blue*	*Awake*
HYH	Red	Sleep	*Green*	*Awake*
CNOT (awake control)	Blue	Awake	*Blue*	*Sleep*
CNOT (asleep control)	Blue	Sleep	*Blue*	*Sleep*

4.3.5. *Post-Activity Questions*

1. What did the cats and their colors represent in this game?
    a. *Answer: The cats represent qubits, the Sleep/Awake represent the state of the qubit, and the different colors are different phases.*

2. What is wave interference? How did this show up analogously in this game?
    a. *Answer: Wave interference is the result when two or more waves are in the same place at the same time and they add together. In this game we represented wave interference when the second H gate was applied which resulted in two cats being in the awake and/or sleep positions.*

3. What is superposition? How did this show up analogously in this game?
    a. *Answer: Superposition is when something is existing in multiple states at the same time. This showed up here when we applied a single H gate and one cat became both awake and asleep at the same time.*

4. What is entanglement? How did this show up analogously in this game?
    a. *Answer: Entanglement is when two things are linked such that they impact each other no matter how far apart they are. This showed up in this game in the CNOT gate in which the control bit affected the target bit.*

5. What did you enjoy about this game?

a. *<u>Answer:</u> Student answers will vary.*

6. What did you find challenging about this game?
   a. *<u>Answer:</u> Student answers will vary.*

5. Design Challenge

<u>The Challenge:</u> Design a QubitCat change challenge using the Save Schrödinger's Cat game.

You have practiced turning cats (qubits) of different colors (phases) into different states and colors. Now it is your turn to design a challenge for your classmates. First, you will choose your cat and its state of being asleep or awake, and then you will try out a series of gates to change either its color or state. Once you have one you like, write it down as a challenge for your classmates: Take a (insert color) Cat that is (asleep/awake) and change it into a Cat that is (insert color) (insert state).

5.1 Design Questions

1. What cat will you choose as your initial cat? Is it awake or asleep?
2. Which gates will you initially use with your cat to change its color or state? Brainstorm a few options and what you anticipate will happen.

<u>Note to teachers:</u> Encourage students to write out their brainstorming to help communicate their ideas to each other and so you can spot any troubles. There will be a large variation in what students will do. Before the students exchange their challenges, check to make sure their answer is correct. If it is incorrect, you can tell them exactly what is wrong or merely say there is an error and leave it up to them. Your choice will depend on how comfortable the students are with working with the gates.

5.2 Design Sketch

Sketch the designs of your cat qubit change below. Write the challenge of the change using: Take a (insert color) Cat that is (asleep/awake) and change it into a Cat that is (insert color) (insert state).

6. Supplemental Activity: Quantum Computing with Python and Qiskit

6.1 Additional Background

Quantum computing is a new paradigm of computation that leverages the principles of quantum mechanics to solve complex problems that are intractable for classical computers. Unlike classical computers that use bits to represent information as 0 or 1, quantum computers use qubits, which can exist in a superposition of both states simultaneously. This, along with other quantum phenomena like entanglement and interference, allows quantum computers to perform certain calculations much faster than classical computers.

In a nutshell two bits of a classical computer can be in four possible states (00, 01, 10, or 11), but only one of them at any time. This limits the computer to processing one input at a time (like trying one corridor in the maze). In a quantum computer, two qubits can also represent the exact same four states (00, 01, 10, or 11) at the same time. Quantum computing is the idea that we can use this quantum rule-breaking to process information in a new way - one that's totally different from how regular computers work.

To start programming quantum computers, you will use Python and Qiskit, an open-source quantum computing framework developed by IBM. Qiskit provides tools for creating, manipulating, and simulating quantum circuits.

6.2 Procedure

1. Before you begin, you need to install Python, Qiskit, and Jupyter Lab. Follow these steps to set up your environment:
    a. Download Python from the official website (https://www.python.org/downloads/) and install it. Make sure to add Python to your system's PATH during installation.
    b. Open your terminal or command prompt.
    c. Use pip, the Python package installer, to install Qiskit (‘pip install qiskit’).
    d. Use pip, to install a tool to visualize Qiskit (‘pip install pylatexenc’)
    e. Use pip (or another method: https://jupyter.org/install), to install Jupyter Lab (‘pip install jupyterlab’)

f. Open a Python interpreter by typing python in your terminal. Import Qiskit modules to verify the installation ('import qiskit' then 'print(qiskit.__version__)').

2. Create simple quantum circuits to generate a superposition state and an entanglement state, which is a fundamental concept in quantum computing. Here's how you can do it in a Jupyter notebook:
   a. Import the required Python packages.
      i. *import qiskit as q*
      ii. *from qiskit import quantum_info as qi*
      iii. *from qiskit import QuantumCircuit*
   b. Instantiate the quantum circuit class.
      i. *qc = QuantumCircuit(2) # the argument (2) represents 2 qubits we're going to work with*
      ii. *qc.draw(output = 'mpl')*
   c. Instantiate the quantum circuit class.
      i. *state_0 = qi.Statevector(qc)*
      ii. *state_0.draw('bloch')*
   d. Apply different gates on these qubits using different methods such as x, h, etc.
      i. *qc.x(0) # x gate is applied on the first qubit*
      ii. *qc.h(1) # Hadamard gate on second qubit*
      iii. *qc.draw(output = 'mpl')*
   e. Visualize the output of these circuits. (#to find out the output vector at the output of the circuit. let's name the state vector state_1)
      i. *state_1 = qi.Statevector(qc)*
      ii. *state_1.draw(output='bloch')*
   f. Apply a CNOT gate on the first qubit.
      i. *qc2 = QuantumCircuit(2)*
      ii. *qc2.x(0) # x gate on the first qubit ...*
      iii. *qc2.cx(0, 1) # CNOT gate on first qubit ...*
      iv. *qc2.draw(output = 'mpl')*
      v. *state_3 = qi.Statevector(qc2)*
      vi. *state_3.draw('bloch')*

7. Sources

Quantum computing background

- https://www.ibm.com/think/topics/quantum-cryptography
- https://risingwave.com/blog/beginners-guide-to-quantum-computing-for-dummies/
- https://www.youtube.com/watch?v=tsbCSkvHhMo

BB84 protocol

- https://arxiv.org/pdf/2110.01402

Save Schrodinger's Cat

- https://www.youtube.com/watch?v=1OEqjGWOUhM&ab_channel=PhysicsCentral
- https://www.aps.org/learning-resources/save-schroedingers-cat