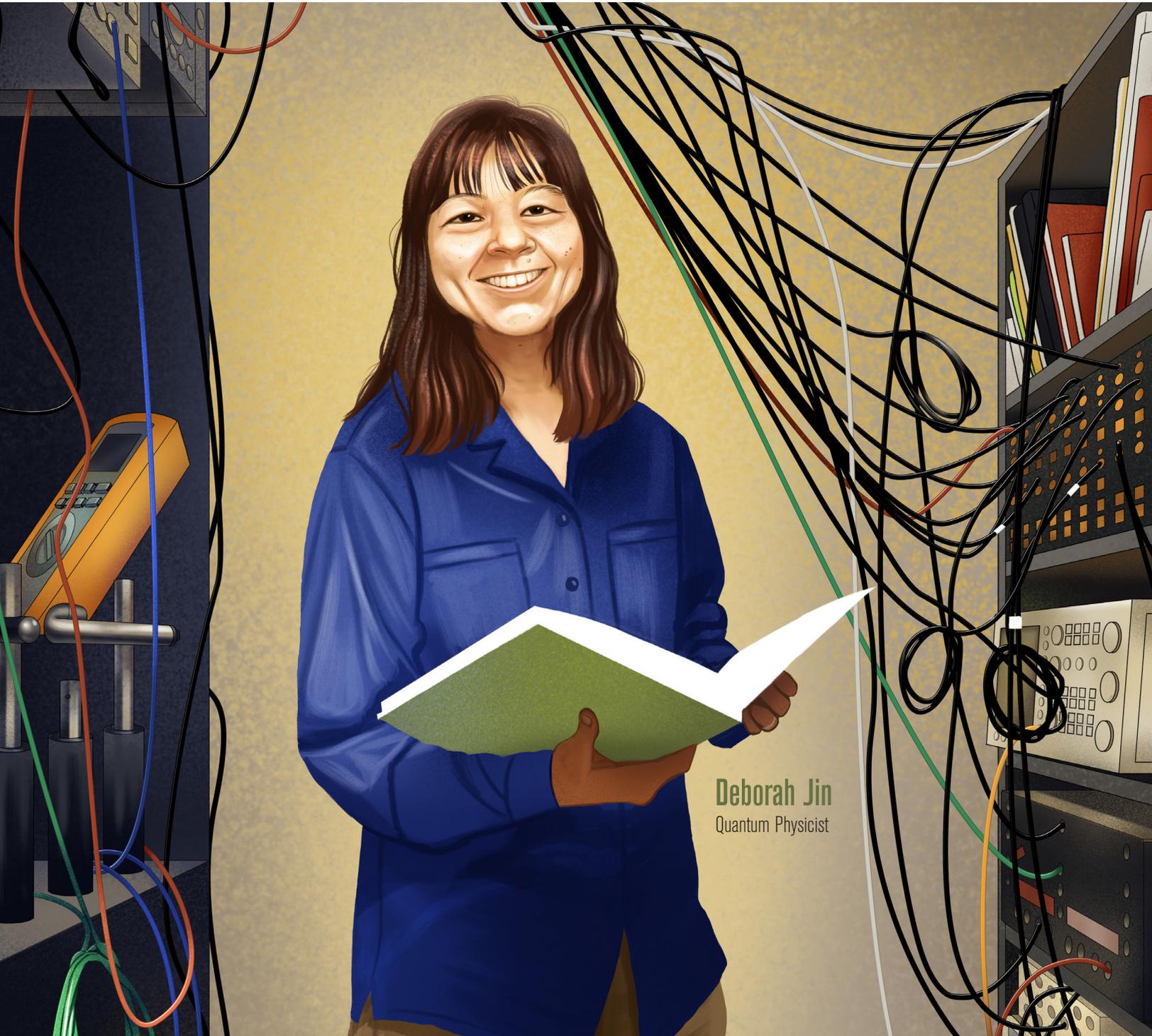


# PhysicsQuest 2021

Science Kits for Middle School Classrooms

Introduction to the World of Quantum



Deborah Jin  
Quantum Physicist

Distributed by the American Physical Society

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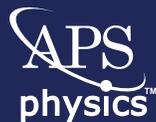
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# Welcome to PhysicsQuest 2021!

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When we look at the world around us, everything is made up of atoms. Usually these atoms organize to form four different types of matter: solids, liquids, gases, and plasmas—all part of what we see every day. However, if you were to shrink down to the size of an atom, you would see that atoms and the even tinier pieces that make *them* up (called subatomic particles) behave in strange ways that don't match up with what we might expect. The study of matter at this scale is called quantum mechanics. In this PhysicsQuest kit, you will explore concepts in quantum mechanics, from the behavior of light to how the strange world of atoms can be harnessed to create a new type of computer.

Studying atoms can get even weirder when they are manipulated with lasers or made super cold. In this kit, you'll also learn more about the work of Dr. Deborah Jin, a quantum scientist who used lasers and magnets to cool down atoms and make new states of matter.

## For Teachers

There is a guide available online for teachers and/or parents with videos, additional resources, and supporting materials for the content presented in this guide. You can find it online at **physicscentral.com**.

## About the American Physical Society (APS)

The American Physical Society is the premier professional society for physicists in the United States. APS shares the knowledge of physics by publishing journals, hosting scientific meetings, reaching out to the public, and promoting physics education.

PhysicsQuest is brought to you by PhysicsCentral, an APS program that communicates the excitement and importance of physics to people of all ages.

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# About Dr. Deborah Jin

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## Physics Family

Deborah Shui-Lan Jin was born November 15, 1968 into a physics family: her parents were both physicists. She was one of three children, and one of two who would become a physicist, along with her brother also studied physics. Growing up in Florida near where her father was a professor, Jin competed in—and won—many math competitions. She also felt inspired by her parents from a young age to learn more about physics.

Jin went to Princeton University to study physics, where she immediately stood out for both her school work and research. She took a summer job at NASA's Goddard Space Flight Center, where she decided once and for all that she really did want to become a physicist. After getting her degree in 1990, Jin went to the University of Chicago in Illinois to study for her PhD. While she was there, she met another physicist, John Bohn, whom she married, and sometimes collaborated with on experiments.



## Famous Physicists

Jin graduated with her PhD in 1995 and decided to go work at JILA in Boulder, Colorado with Eric Cornell, who is famous for winning a Nobel Prize in 2001. To work with Cornell, Jin changed the type of physics she studied, going from solid state physics—a type of physics that studies solid matter and is the basis for creating new kinds of materials—to a branch of physics called atomic, molecular and optical (AMO) physics, which involves studying the behavior of atoms at extremely cold temperatures. Ultracold atoms have the potential to be used in superpowerful, superfast computers called quantum computers; quantum computers have the potential to solve problems that normal computers can't. While she had to learn new skills at her new job, Jin quickly impressed Cornell and other physicists in the AMO community.

In 1995, Cornell and a University of Colorado professor Carl E. Wieman had just observed something that has been called a fifth state of matter: a Bose-Einstein condensate (BEC). They did this by creating a gas of particles called bosons and cooling it so much that all of the bosons slowed down so much they almost stopped moving, and then melded together to act like one bigger particle. Once she joined Cornell at JILA, Jin led the first studies of this new type of matter.

## Another New Kind of Matter

In 1997, despite getting lots of offers to work somewhere else, Jin started her own research group at JILA to work on an even harder experiment. Jin wanted to make another super cold gas, this time using a type of particle called fermions, to make fermionic condensate, a state of quantum matter similar to the BEC. This was a bigger challenge than making a BEC, because bosons like to interact and bond together more than fermions do. However, in 2003, Jin became the first person to ever see this type of matter.

In 2008, she partnered with another JILA scientist named Jun Ye to study ultracold gasses made up of molecules—instead of just atoms, like bosons and fermions. Using lasers and magnetic fields, they carefully controlled atoms as they tried to bond into molecules, allowing them to look at the fundamental nature of chemical reactions.

## Leaving a Legacy

During her career at JILA, where she worked for nearly 20 years, Jin accomplished exciting physics and won all kinds of awards. Her research was important to the field of AMO physics and has left a lasting impact.

Jin sadly died in 2016 at just 47 years old, but, in addition to her scientific work, she also left a legacy of inspiring other physicists. She mentored 16 PhD students and even more post-docs and made sure to encourage other women to pursue their talents and interests in science to the best of their ability. She also made sure to share her love of physics with her daughter, Jaclyn, as they were both huge fans of reading Spectra comics.

## ACTIVITY

## 1

# Mystery Tube

Have you ever wondered how scientists figure out how things work when they do not have a direct way of measuring the phenomena? For example, how do we know that the structure of an atom consists of electrons revolving around a positively charged nucleus, like the planets around the sun? In this activity, we will learn how to build scientific models based on observations, realize that different models can explain the same observations, and refine our models based on new data.

## KEY QUESTION

What is a scientific model and how do we create one?

## Experiment

To start off, look at the mystery tube you have in front of you and play with it. What kinds of things can you observe about the tube? With your friends, design an experiment that will allow you to develop a model of the mystery tube. Your model should represent how the mystery tube looks like inside. Use the scientific method to guide the design of your experiment.

The scientific method has five basic steps, plus one feedback step:

- Make an observation.
- Ask a question.
- Form a hypothesis, or testable explanation.
- Make a prediction based on the hypothesis.
- Test the prediction.
- Iterate: use the results to make new hypotheses or predictions.

## Materials

- A mystery tube
- Paper/whiteboard to write your observations

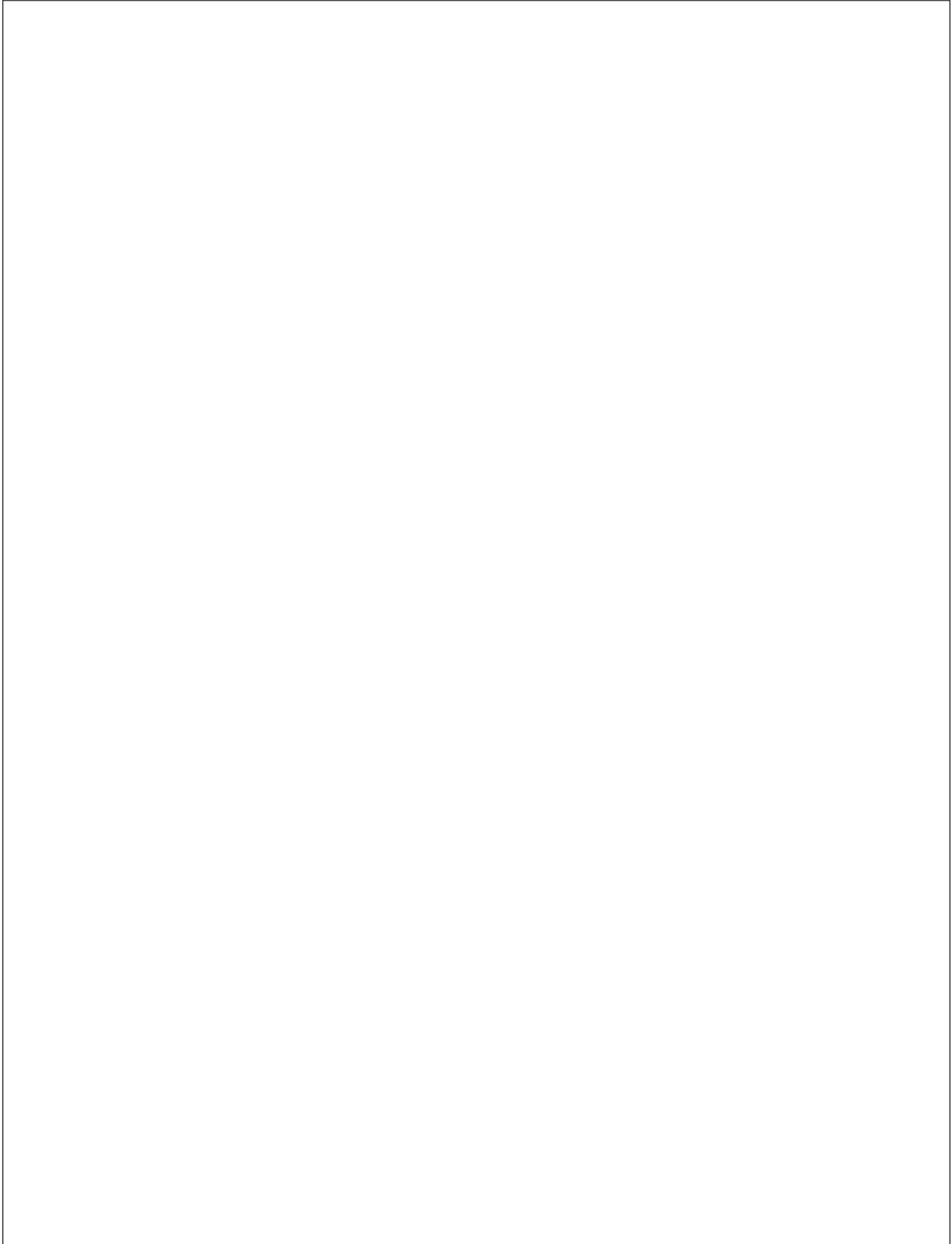
## Setting Up

Before you start collecting data, develop a list of all the different things you can test and write different hypotheses or predictions about what you expect to see for the different tests. To collect data for the experiments work with your group. In creating the design, think about what is the data that you need to collect and how many times do you need to repeat the experiment to be sure. What are the variables that you are going to test? Which variables will you keep constant and which ones would you change? Once you have a plan, grab the mystery tube and start testing!

## Collecting Data

Write on your notes the test you are doing, what variable you are testing, your hypothesis, and your observations after completing the test. What was the result of the experiment? Did you get the same result every time? Why do you think that is? Any other observations?

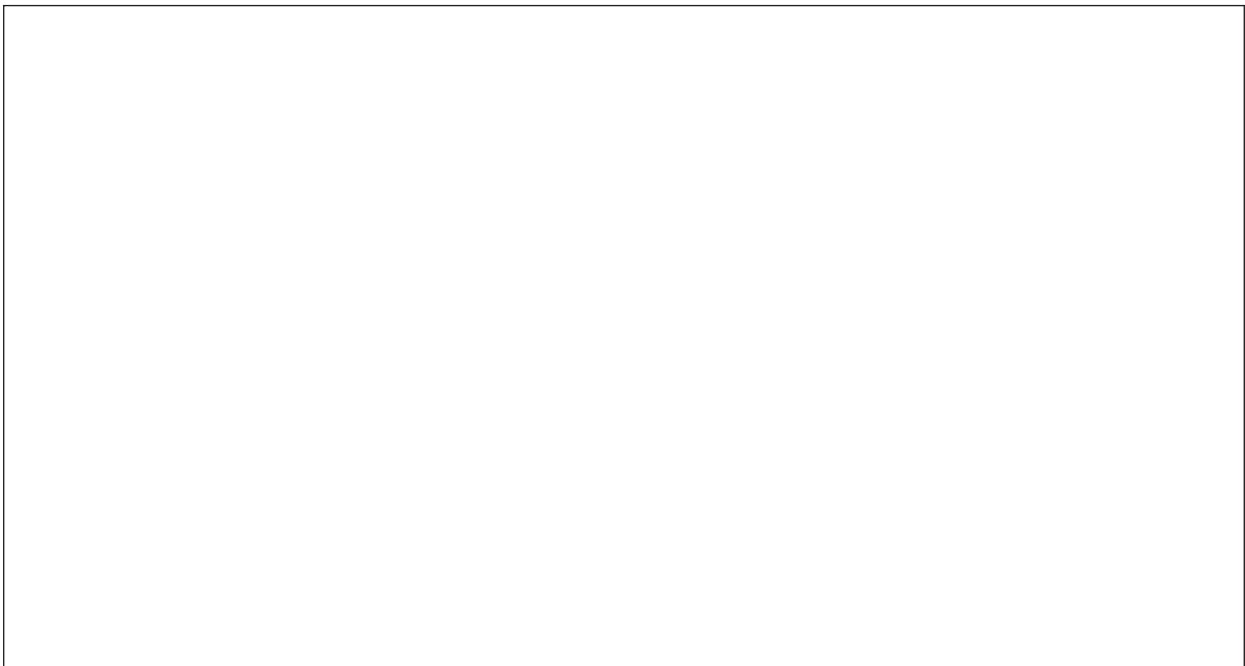
Draw in your notes a diagram of your initial model and explain how the model supports the observations.

A large, empty rectangular box with a thin black border, intended for a student to draw a diagram and provide an explanation. The box occupies most of the page's vertical space.

Check your results with the other groups in your class and with your teacher. What are other groups' models like? Do their models work better at replicating the observations? Can you refine your model with the new information from your observations of your peers' models? Write your notes.



Once your team has decided on a model, ask your teacher for the materials you will need to build your model. Repeat all the tests you did with the original mystery tube with your built model. Write your observations.



## Analyzing Your Data

With the class, define a method for testing the accuracy of the models you and your peers' created. Then use that method to assess your model and your peers' model. Determine how good are the different models are at predicting the observed behaviors and explaining the data collected from the original mystery tube. With your team reflecting on what you learn about models, could we get the same results with different models? Can finding more data allow you to refine the model and get better results? Do we always have a way to have a perfect model? What examples can you think of in which you have used a model to learn about something or explain something to someone else?

# Particle-Wave Duality

What is light? Have you ever wondered if light always travels in a straight line or if it spreads in multiple ways? We know that scientists use experiments to develop an understanding of the world around us. We propose hypotheses and design experiments to test them or we ask questions like why do objects/ things always fall to the ground. Often the technology that we can use to do our experiments changes and evolves, which allows us to refine our experiments and therefore expand our knowledge and understanding of the world. One of the initial questions scientists pondered in the early 1700s was what is light and how it travels. For many many years, there were different theories, and physicists designed many experiments to confirm the different theories. Today you are going to follow their paths to figure it out by yourself.

## KEY QUESTION

What are the models that best explain the behavior of light? Does light behave like a wave, a particle, neither, or both?

## Experiment

To start off, consider what question you are looking to answer and what hypothesis you need to test. With your group, design experiments that will allow you to develop a model that explains the behavior of light. What do you know about how particles and waves behave? How can you test the behavior of particles and test under similar conditions? Use the scientific method to guide the design of your experiment.

The scientific method has five basic steps, plus one feedback step:

- Make an observation.
- Ask a question.
- Form a hypothesis, or testable explanation.
- Make a prediction based on the hypothesis.
- Test the prediction.
- Iterate: use the results to make new hypotheses or predictions.

## Materials

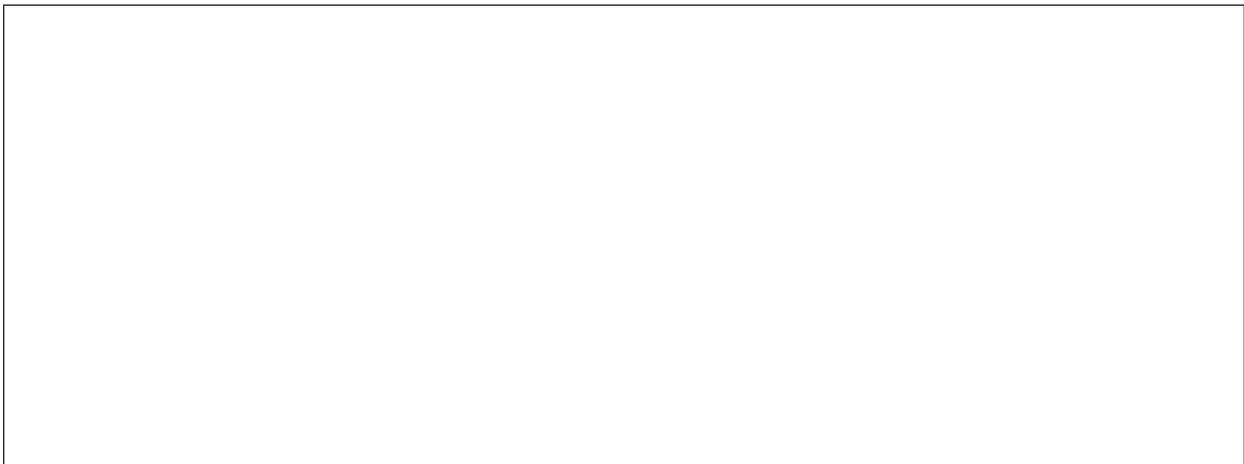
- Laser pointer, a red laser works best because of its longer wavelength
- Thin copper filament/wire about 5 cm long
- Electrical tape
- A place to write your observations

## Setting Up

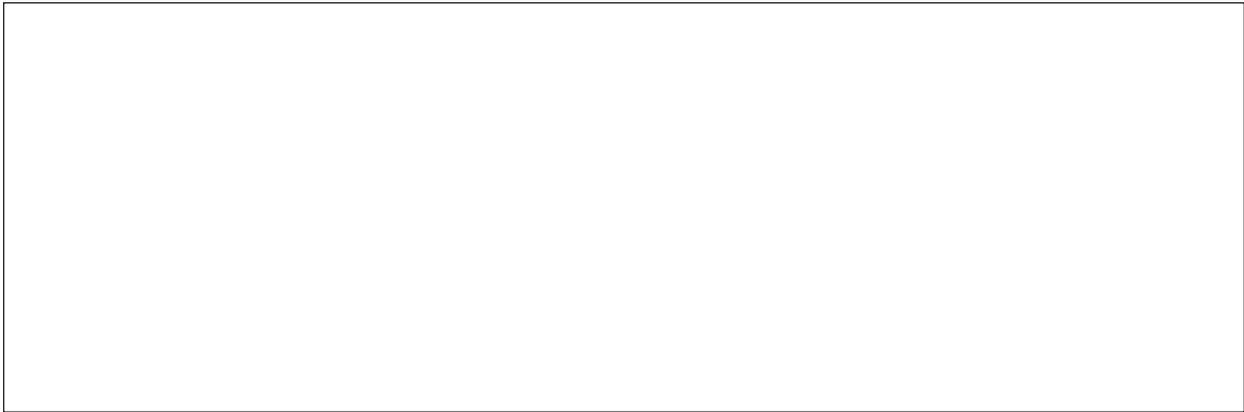
Before you start collecting data, develop a list of all the different things you can test and write hypotheses or predictions about what you expect to see for the different tests. In this case, you should think about an experiment that can help you test how particles behave, how waves behave, and finally, how light behaves, to compare your results. To collect data, work with your group. In creating the experiment design, think about what data you need to collect and how many times you need to repeat the experiment to be sure. What are the variables that you are going to test? Which variables will you keep constant, and which ones would you change? We propose that you think about how particles and waves would behave if they have to pass through some obstacles. Then design an experiment to see how light propagates after it passes through an obstacle, like a double slit. Once you have a plan, grab the materials you need and start testing!

## Collecting Data

As with the previous experiment, write in your notes the tests that you will be doing, what variable you are testing, and your hypothesis. To start, how do you think light looks when projected on a wall? What about a laser pointer? Now, what do you think will change when you make the light go through a double slit? The laser? Draw in your notes a diagram of your initial models for both scenarios.

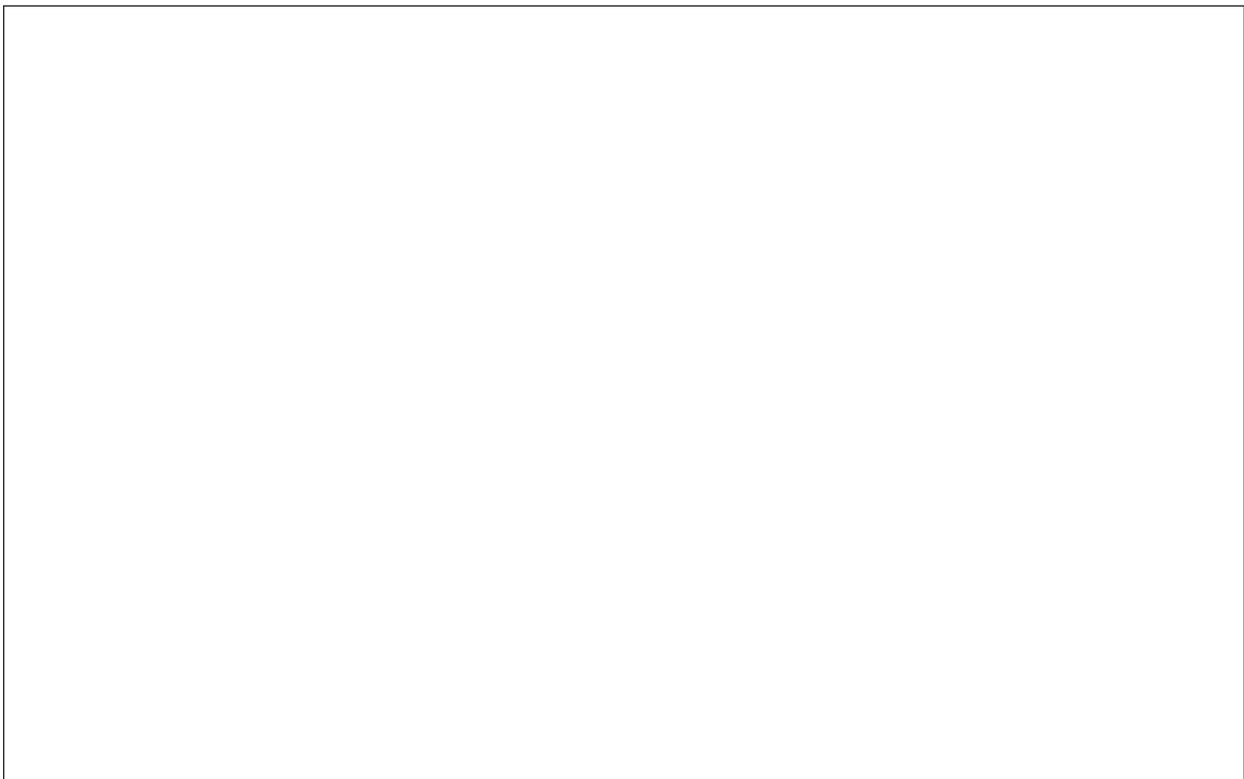


Think about how your model of the light is similar or different from what you found with the wave and particle experiment. Write down your hypothesis.



Then design your experiment. We are using a laser pointer to test the behavior of light. With the materials given, how can you test how light behaves when it goes through a double slit? In this case, we give you a bit more help to set up your experiment. To build your double slit set up for the laser, take the piece of copper wire and place it across the laser pointer, where the beam comes out. Then use the electrical tape to secure the copper wire to the laser pointer on the top and bottom. Then add extra tape to make a smaller aperture for the beam to go through.

**Be careful to not shine the laser on people's faces or eyes.**

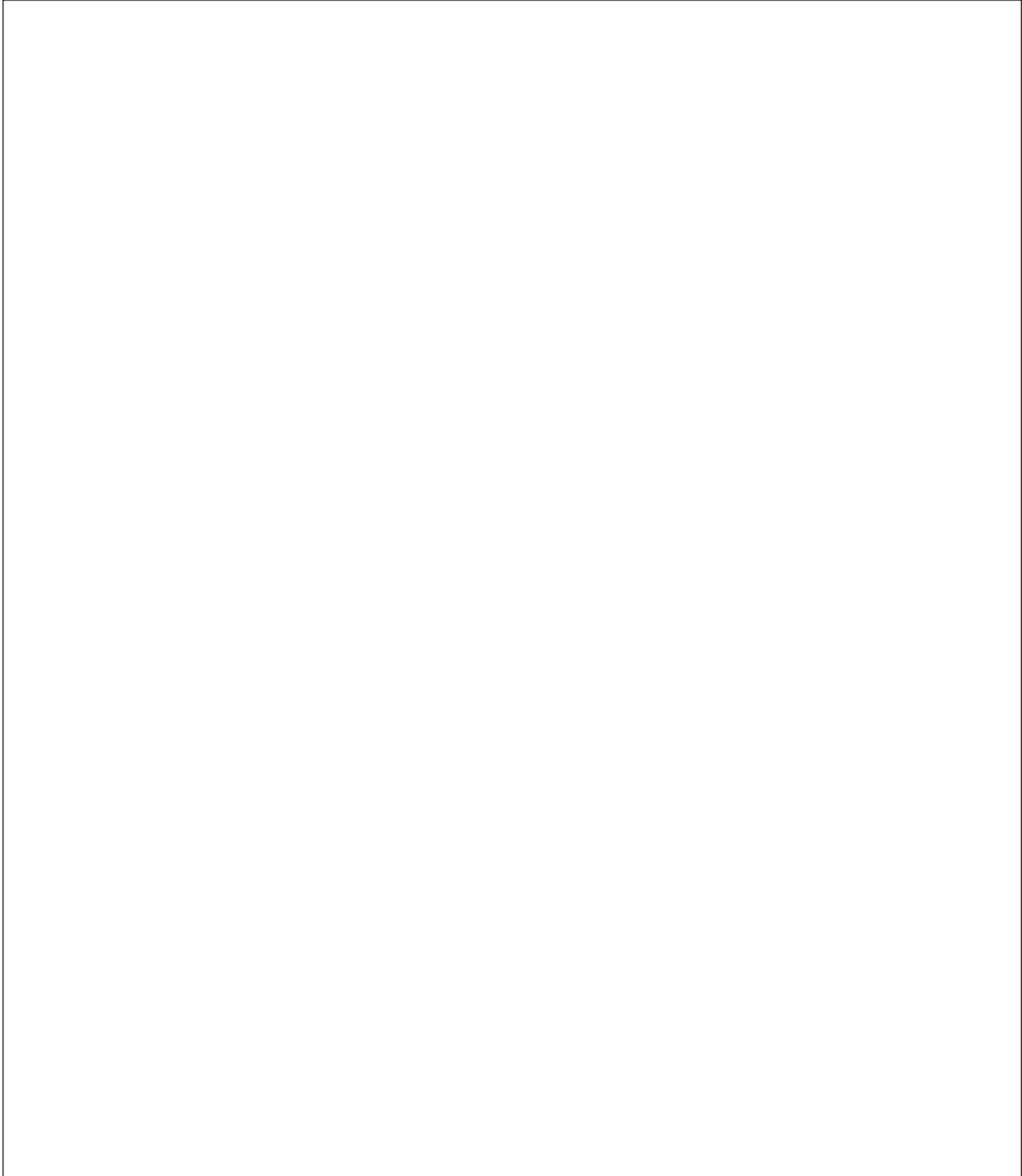


Once you have your experiment setup, start your test. Remember to repeat the tests more than once. Write down your observations after every test. What was the result of the experiment? Did you get similar results every time? Why do you think that is? Any other observations? How did your model compare to your observations? How did your observations compare to what you saw on the particle and wave experiments? Write your answers.

## Analyzing Your Data

Check your results with the other groups in your class and with your teacher. What are other groups' models like? Are their models similar to yours or different? Can you refine your model with the new information from your observations of your peers' models? Write your answers.

With your class, discuss how good the different models are at predicting the observed behaviors and explaining the data collected. Reflect on what you learned. Could we get the same results with different models? Can finding more data allow you to refine the model and get better results? Finally, as a class, define a model for how light behaves when it goes through a double slit, using your observations and your peers' observations to select the model that best describes the behavior of light going through the double slit. Write or draw what the final model looks like.



## ACTIVITY

## 3

# Save Schrödinger's Cat

Have you ever wondered how modern computers can do so many different tasks, like stream movies or connect to other devices? How can computers perform tasks which appear to differ from each other widely?

This is because computers are all built to use the same logic and the same assessment criteria to understand each other. Instructions the computers use for achieving tasks are called **logic circuits**. The result of executing any such circuit will always have just one of the two states: **False** or **True**. We can call these two states any way we want, including Asleep and Awake. The building blocks of these circuits are the **logic gates**. A programmer's job is to build circuits that expand the capabilities of computers. For example, finding new ways to construct circuits that flip between False and True creates more elaborate logic gates to create even more advanced logic circuits.

In the board game "Save Schrodinger's Cat," you play the role of the programmer. You will build logic circuits by placing gates in a sequence to prevent the Challenge Scenarios' outcomes from happening to our beloved cat. We want our cat to always be in the Awake (True) state after each challenge. Getting there is entirely up to you and your ability to master various logic gates and develop useful circuits to achieve this goal.

There is a catch, however. The logic gates you use in this board game go beyond what classical computers can do today. We need additional logic to play with to go beyond the laws of quantum physics. We need this additional logic since the cat can be in states that require going beyond our usual logic to resolve. This extension to standard computer logic comes from our understanding of quantum physics.

The laws of quantum allow for the cat to be both Asleep (False) and Awake (True) simultaneously, through a phenomenon called **superposition**. Both states, Asleep and Awake, can also have a **quantum phase** (represented by the colors on the cat tokens). To save the cat, you will have to get familiar with what all these logic gates do and create logic circuits that can work beyond classical computers. One way to do so is combining superposition and transition through various quantum phases throughout the challenges to reproduce a new phenomenon called **Quantum Interference**. You will achieve this if you manage to collide cat tokens in a superposition state with the proper quantum phases.

First, look at all the quantum gate cards that come with the board game. The most basic card is the X gate. The X gate flips states from Awake to Asleep and vice versa. The Z, S gate cards do not flip the position but change the color of the cat tokens. The Y and H gates flip from Asleep (False) to Awake (True) and add color (quantum phase) to your circuit. The most exciting card is the H gate, which can create superposition and achieve quantum interference.

All these cards are called **quantum logic gates**, and these require a quantum computer to run them on. Why quantum? Because as bizarre as this may seem, this set of logic gates appears to be the exact settings needed to describe all events occurring in our Universe. In this board game, our beloved cat is bound by the state of an atom that follows quantum logic. In this game, you will master through experimentation the quantum logic of our Universe and become able to write logic circuits that can prevent undesired events from happening.

## KEY QUESTIONS

What are logic gates? What is a circuit?

What are quantum logic gates and how do you use them to give instructions to a quantum computer?

How is quantum logic fundamentally different to our classical, computer logic?

What are the key phenomena that make people excited about quantum computing?

Can you describe quantum interference after playing?

## Game

1. Before you start, look at all the cards called gates that come with the board game. Can you spot which of these gates do classical logic (flip states from Awake to Asleep and back, without adding color)? Which do quantum logic (add phase or create superposition)?
2. Look at the Challenge scenario cards. Each scenario card is the first card you need to place on your desk, and the cat token should be placed as indicated on top of it.
3. Remember that the winning condition is to obtain a single blue cat token on the Awake state. To succeed, you need to decide which gate cards to place below the scenario card to create a quantum circuit that achieves the winning condition.
4. Look at the four cat tokens and flip them to see both sides. The four colors of these tokens represent the four types of quantum phase possible. You will use these tokens to navigate the quantum gates by following the arrows and the colors shown on each gate. The colors change according to the Color Legend table. The H gate has its own quantum rules, presented in the Quantum Interference table.

## First challenge:

For the first challenge, flip the state of the cat from Asleep to Awake. Such simple tasks do not require the use of quantum logic gates. Do you need more than one logic gate, or can you solve this with just one?

### Learning Question:

These X gates are what our computers use today to flip from True to False and back. Think about what is happening here. Do you need quantum mechanics to explain what happened, or could this have been something that happens to an ordinary cat and without referring to quantum logic?

## Second challenge:

Now, find a sequence of quantum gates that can do the same thing you have achieved previously, but without using the X gate this time. One possible way to accomplish this is to place the cat tokens in superposition. By changing the color to red and then collapsing the superposition, you will resolve this demanding task! Pay close attention to the Quantum Interference table when you play with H gates.

### Learning Question:

This challenge shows that you can build up all regular computer logic gates with some quantum gates, but what about the other way around? It turns out quantum logic can completely contain all our ordinary computer logic but is the reverse true? (i.e., can you use X gates to build an H gate?).

## Third challenge:

Our cat is in superposition! We need to use quantum gates to collapse the cat tokens such that we obtain a single blue cat token at the end. Once we have obtained a single blue cat token, we can use regular computer logic to bring it to the Awake state. What is the smallest number of gates needed to achieve this?

### Learning Question:

Since the quantum object is in superposition before we add any quantum logic gate, does this mean humans invented the phenomena of superposition? Or, because it occurs in nature, did we discover it and later found out how to harness its power to build logic?

## Fourth challenge:

This challenge will test your mastery over the Color Legend table. If this token were blue, a simple X gate would suffice to save the cat. Are you able to find the shortest quantum circuit that can change the cat token's color to blue and bring it to the Awake state?

### Learning Question:

What is different about the cat in this challenge? Could you ever get the green cat to go into another state (Asleep versus Awake) based on it being green rather than blue? If you can only tell whether the cat is asleep or awake, but not the phase (the color), could you ever tell what the starting color was? In other words, does this color mean anything in the classical world?

## Fifth challenge:

This challenge will test your ability to make use of the complete set of quantum logic gates available. Start with four tokens on the table to account for all possible changes that the quantum gates of your choice will bring. To solve complicated challenges such as these, start "thinking quantum" and develop an intuition for it. What is your approach? Do you choose to place an H gate first to collapse the cat tokens and work with fewer cat tokens, or do you prefer to change their color first (place Z or S gates first)? What is the shortest quantum algorithm that can resolve this challenge?

### Learning Question:

How does this challenge relate to the third challenge? How is it different? Can you explain why the Z, S gates are useful when used in combination with H gates?

## Make your own challenge:

Pick any starting set of tokens and challenge your friends to find a quantum circuit that can save the cat. Challenge them to find the one that uses the least number of cards! If you want to go deeper into the world of quantum, try the Quantum Odyssey video game linked below.

This board game is based on the rules of a videogame called Quantum Odyssey (<https://www.quark-sinteractive.com/>) designed to immerse the player in the world of quantum physics and teach quantum computing using powerful visuals.

# Game Instructions for Save Schrödinger's Cat

Based on the rules of a videogame called Quantum Odyssey by [quarksinteractive.com](http://quarksinteractive.com)

Dr. Schrödinger is conducting a classic quantum experiment! He has built a steel chamber in which he has placed a Geiger counter along with a tiny bit of radioactive substance, an amount so small that perhaps in a matter of minutes one of the atoms will decay, but perhaps, with equal probability, none of the atoms will decay. If this does happen, the counter tube will discharge, then through an electromagnet activated by a signal, release a hammer that shatters a flask of sleeping gas.

Dr. Schrödinger leaves the office for the night to feed his cat.

You are his lab assistant, and you are certain that if one of the atoms decays, the flask would surely break inside the steel chamber and the gas would put everything inside the chamber to sleep. As you ponder upon the experimental details, you hear a sudden "Meow!" coming from the steel chamber.

Oh no, Schrödinger's Cat must have sneaked inside the chamber searching for food!

You must quickly use your knowledge of quantum and Save Schrödinger's Cat!

## How to Win

The purpose of the game is to start from one of the **Challenge Scenarios**, place the **cat token** as indicated in each scenario and then figure out and place down the right sequence of **Quantum Gates** to create a quantum path for the cat token to arrive from the initial state (given in the Challenge Scenario) to our desired final state: a single **blue** cat token on the **Awake** state. This will stabilize the atom and keep Schrödinger's cat awake.

You win a Challenge if you manage to obtain on the last card a **single, blue-colored token** at the end of an uninterrupted sequence of quantum gate cards.

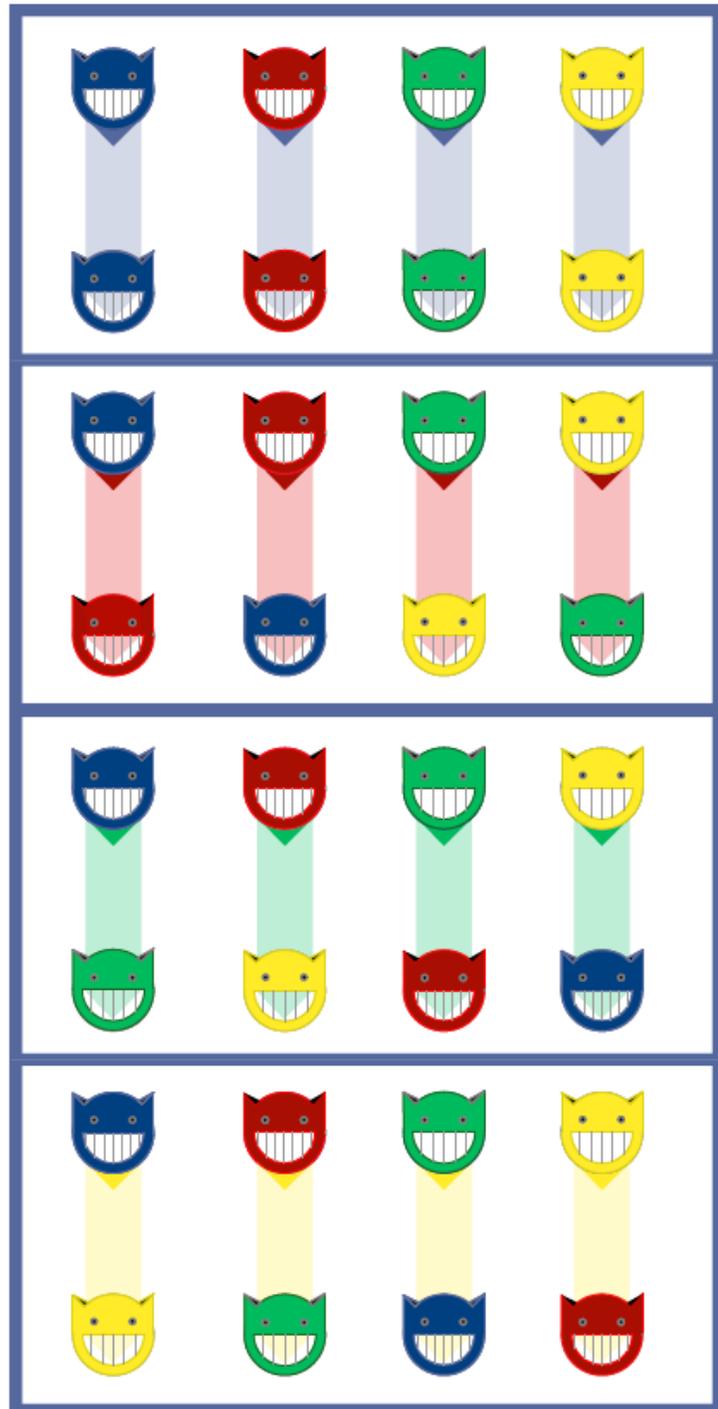
All quantum gates you placed should remain in place until you solve the Challenge Scenario. They represent the **Quantum Algorithm** you create to achieve the final state (blue cat token on the Awake state) out of an initial state given by the Challenge Scenario. There is more than one way to solve a problem!

## Game Components

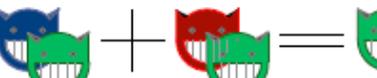
1. **The colors** in the game represent the quantum phase! There are 2 types of tokens: 4 **blue-red** tokens (blue on one side and red on the other), 4 **green-gold** tokens (green on one side and gold on the other). **These 8 tokens**, through their position and color, represent quantum states of the atom that decide the fate of Schrödinger's Cat!
2. The **Color Legend** table shows the rules for *phase interactions*.
3. The **Quantum Interference table** (next page) shows the behavioral rules of what happens to the quantum state inside an H gate. You will need an H gate when you want your tokens to be in a superposition of both SLEEP and AWAKE or create phase interference between the tokens.

**Quantum Interference table:** use **only** to calculate the quantum state of your cat inside an H gate

### Color Legend



# Quantum Interference

## Game Setup

### Rules of the game:

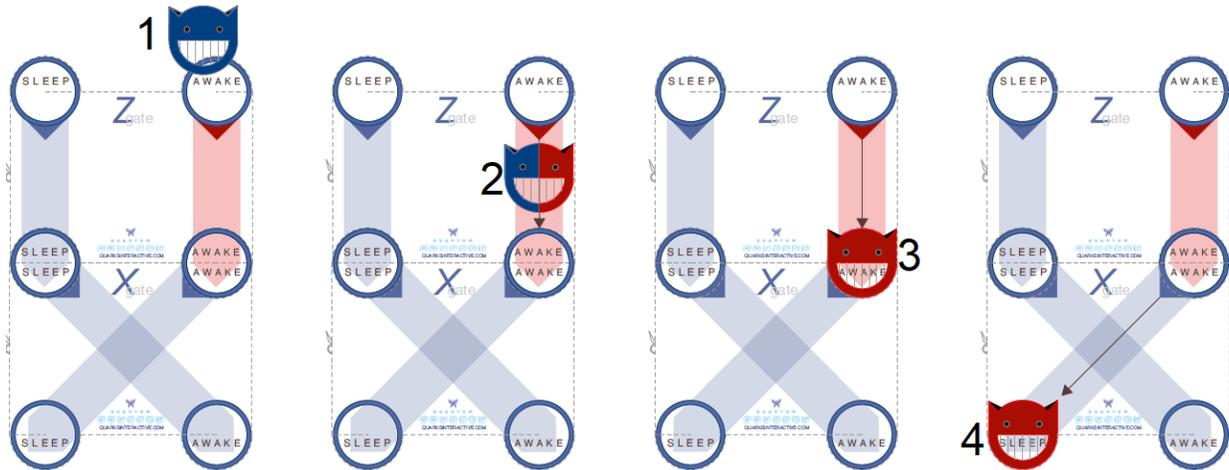
1. Place on a flat surface one of the Challenge Scenarios to start and the Final State card that shows the winning condition.
2. Place the cat token(s) as indicated by the Challenge Scenario.
3. Pick from the quantum gate cards those that you believe will bring the token closer to the Final state. Place these gates one below each other, from the Scenario card to the Final state card.
4. Navigate the quantum gates with the token. Follow the paths as indicated by the arrows. If one of the paths is a different color, look at the **Color Legend** and change the color of the token as indicated by the **Color Legend**.
5. Try to find the right combination of quantum gate cards to reach the Final State. The final combination of gates used is your quantum algorithm. Try to find the optimal one (to reach the Final State with the least number of gates).
6. A special case: **The H gate:**

You can create additional tokens, combine them, or remove tokens using the **H gate**. This gate has two arrows pointing out from each state and two arrow pointers arriving to each state. For each state on the H gate, add another identical copy of the same token(s) that are already present on that state to be able to travel both arrows simultaneously. When the tokens collide, use the **Quantum Interference** table to calculate what tokens are left!

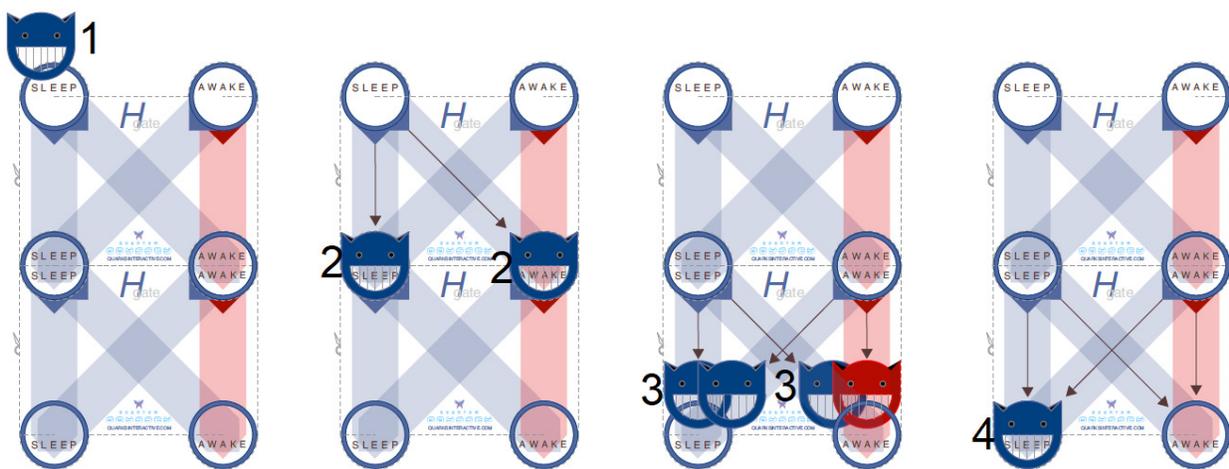
### Two examples of navigating quantum gate cards:

Case 1: blue cat token on Awake state entering a Z gate, followed by an X gate. The output will be a red cat on the Sleep state.

**ZX Sequence:** (1) Place **blue token** on the Z gate's AWAKE state, (2) Token will navigate a **red** path, flip it according to the Color Legend, (3) The now **red token** enters X gate on the AWAKE state, (4) Token crosses from the AWAKE state to the SLEEP state, through a **blue** path (according to the Color Legend).



**HH sequence:** (1) Place **blue token** on the H gate's SLEEP state, (2) There are two arrow pointers in the SLEEP state within the H gate. You must duplicate your token on the board (add another one in this case). Tokens now navigate both paths of **blue** color (nothing changes according to **Color Legend**) at the same time. (3) In this step, you must repeat step (2) from **both SLEEP and AWAKE** states of the second H gate, to have four tokens in total. Take notice that one of the paths from the AWAKE state is of **red** color, which will flip one copy of the token from **blue** to **red**. (4) Use the Quantum Interference table to calculate what happens to the colliding cats from step (3)! Two **blue** cats colliding will leave a single **blue** one, while a **blue** and a **red** cat will result in no cats.



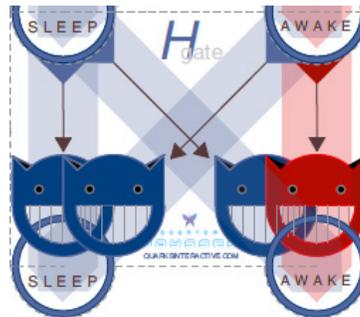
## Color legend table:

These are the rules for what happens to a cat token when it navigates a path of a specific color. Remember there are two types of tokens (blue-red and green-gold).

### Useful tips for colors:

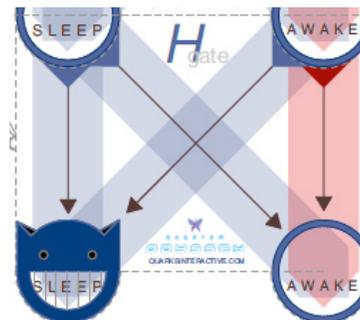
1. The blue path is neutral, it preserves the color of the token.
2. The red path will always flip the token.
3. A green cat going through a green path will result in a red cat.
4. A gold cat going through a green path will result in a blue cat.
5. If you know a thing or two about **Complex Numbers**, it could be easier to think of multiplication between complex numbers. For convenience, a **blue** cat is  $1+0i$ , a **red** cat is  $-1+0i$ , a **green** cat is  $0+i$ , a **gold** cat is  $0-i$ . If you know that  $(0+i)*(0+i) = -1+0i$ , this is just as saying a **green** cat goes through a **green** path and comes out **red** (rule 3).

After you decide to place an H gate, you will notice that because of how the paths within this gate are laid out, your cat tokens will collide like what you see here:



Now look at the table on the right. In this example we have two cases: **blue + blue** on the SLEEP state and **blue + red** on the AWAKE state. The table shows you the outcome. Replace or remove the tokens as indicated in the table.

For our example, we are left with a single **blue** cat:



If you know a thing or two about Complex Numbers, these are the rules for addition!

Example: **blue** + **gold** cats = form a **blue** and a **gold** cat together  $1+0i+(0-i)=1-i$

## ACTIVITY

## 4

# Quantum Circuits

Thousands of scientists around the world are working hard to develop quantum computers—machines that can solve certain problems that are far beyond the reach of the world’s best supercomputers. Famous examples of these kinds of problems include code breaking and simulating complex molecules. Unlike ordinary computers, quantum computers exploit the laws of quantum mechanics. Like ordinary computers, the way a quantum computer works can be understood in terms of a few simple logic operations that act on bits of information. By combining many such operations to form logic circuits, one can solve interesting problems. Here we will use a card game to help you design and test your own quantum circuits, along with a few challenges to help you become a quantum scientist.

Today’s traditional computers store information as strings of 0s and 1s. Modern computers process information using “logic gates” that take a group of 0s and 1s as input and produce a new group as output. Those groups of 0s and 1s are called strings of bits, and specific combinations of those bits are the instructions given to computers to perform tasks.

Quantum computers can help us complete some tasks faster and address complex tasks than traditional computers. This is because, unlike traditional bits, quantum bits can be simultaneously a 0, a 1, or a combination of both. Therefore, it is able to do many more computations at the same time.

The following game will help you learn how to build a representation of a computer program. You will stack different types of cards together to form a “logic circuit.” If you design this circuit in the right way, then you could perform useful computations where, for every input bit string, an answer is given by the output bit string. In addition to representing classical information processing (like in today’s computers), we can also use the cards in the game to write a program for a quantum computer. However, this requires following a set of different rules that only apply for quantum. Let’s play the game to learn those rules!

## KEY QUESTION:

How does a quantum computer work?

## Before the Game

Before you start, look at all the types of cards—states and gates—that come with the game. Look at the rules for the different types of gates. Use the game instructions to separate the classical gates (change a bit from black to white and back) from the quantum gates and the state cards. Use the pictorial rules to help you create the winning sequence of cards.

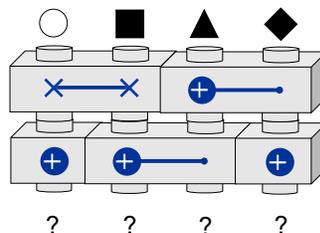
Look at the Warm-up exercises. Each exercise asks you to use the rules of different gates to determine the correct color and shapes for the output of your circuit. You will need to use a combination of gates and state cards to find your answer.

Remember that, to win, you have to find the right combination of gates that will produce the target output, given the initial conditions. To succeed, you will need to decide which gate cards to place below the input state to create a quantum circuit that achieves the winning condition.

## Warm-up Exercises

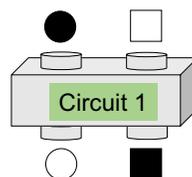
### Classical logic exercise:

Given an input state of one white bit, three black bits, and a sequence of logic gates, use the pictorial rules to determine the output colors—or state—for this circuit.

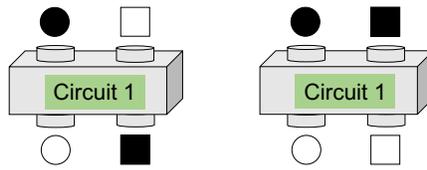


### Circuit-finding exercise:

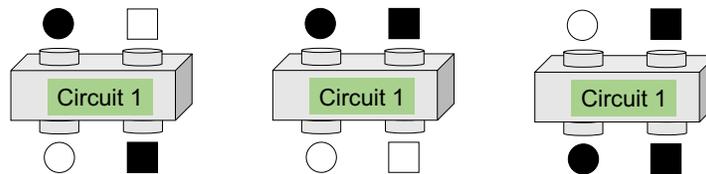
(a) Find at least one combination of gate cards containing no more than two gates each that have the same input/output rule as Circuit 1:



(b) Does your combination of gates from part (a) also satisfy both of these input/output rules? If not, what would you need to change?



(c) Which combination of gates will satisfy all three of the following input/output rules?



### Combining mists exercise:

Combine the following mists (and non-mist) into a single, three-qubit mist.



### Factoring mists exercise:

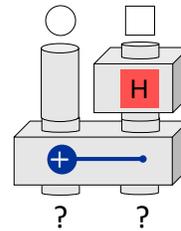
Separate the following mists by factoring them into as many smaller mists/non-mists as possible.



## Entanglement exercise:

Consider the following circuit:

- (a) What is the output state?
- (b) Can the misty state you found be factorized?



## Playing with your friends:

Now that you are familiar with the gates and states and how they work, you can get started. Look at the game instructions. Choose your opponent. One player randomly chooses an initial state card that is used by every player as a starting point. Then, each player selects a secret state card. Challenge your friends to find a quantum circuit that will give you the secret state. There are two ways of winning, solving the circuit before your friends solve theirs or finding a solution that uses the least number of cards!

### Additional Resources

A nice introduction to quantum information using the pictorial formalism described here can be found in the book *Q is for Quantum* by Terry Rudolph. A PDF copy of Part I of the book is available for free at [qisforquantum.org](http://qisforquantum.org). Keep in mind that the book uses a slightly different notation ('NOT' instead of 'X' and 'PETE' instead of 'Hadamard'). Also, all qubits are represented by circles instead of different shapes.

An introduction to quantum superposition can be found in a six-minute excerpt from a video called [Dr. Quantum](#).

# Pictorial Rules for Quantum Circuits

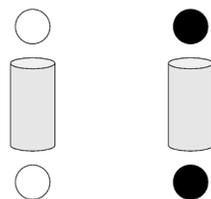
## Pictorial Rules

**Bits** are represented by geometrical shapes like circles, triangles, and squares. Bits are stored on different physical objects of a circuit, such as conductors inside a regular computer. The color of these shapes, white or black, indicate whether each bit is 0 (white) or 1 (black).

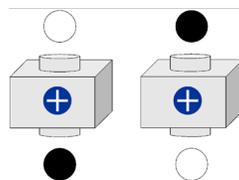


**Gates** are elements of the circuits that allow a signal to pass or not (like an on and off switch). There are different types of gates, each has a specific function.

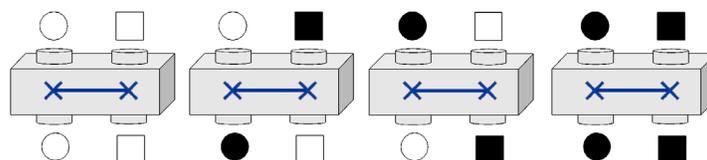
**Identity gate** is labeled by two parallel lines. The identity gate does not change the bit.



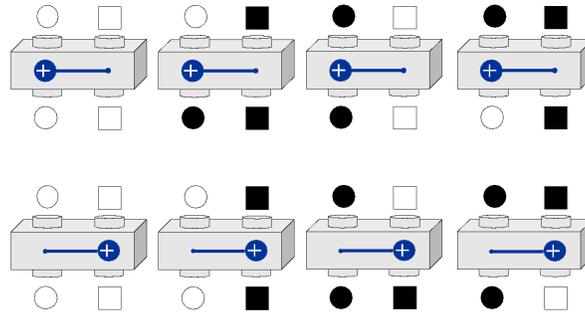
**NOT gate** is a square box labeled with a target symbol. The NOT gate inverts the color of the bit



**SWAP gate** is a rectangle label with two Xs connected by a line. It changes the color of all the bits. The SWAP gate can act on two (or more) bits at the same time.



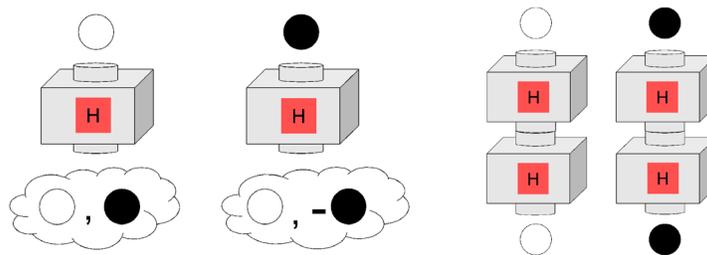
**Controlled-NOT or CNOT gate** is a rectangle labeled with a target symbol on either end of the box and a dot on the opposite side. The CNOT gate changes the color of the bit on the target symbol side only when the color of the other bit is black (1).



**Quantum bits or Qubits** are equivalent to bits but with special quantum properties: be black and white simultaneously, which is called superposition. A qubit in super position is represented by a mist.

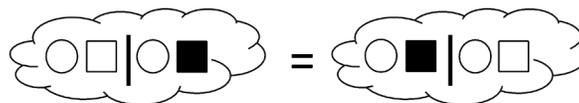


**Hadamard gate** is a quantum gate, which can create superposition states. It is represented by a square labeled with an H. In addition to producing mists from non-mists, the Hadamard box can also do the opposite: It can turn mists into non-mists. This also means that if we stack two H boxes, we find that the circle returns to its original color



### Mist rules:

**Entry order doesn't matter:** Order of the different entries within a mist does not matter



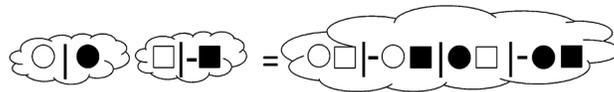
**Cancelling entries:** If two equal shapes are the same color but with opposite signs, then these bits cancel and can be removed from the mist.



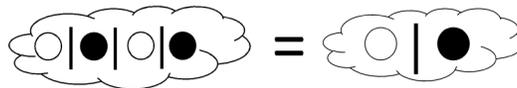
**Removing inner mist:** Mists within mists can be eliminated.



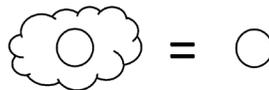
**Combining mist:** Two or more mists can be combined into a single mist in a manner that is identical to the FOIL ("firsts, outers, inners, lasts") mnemonic in algebra, e.g.,  $(a + b)(c + d) = ac + ad + bc + bd$ .



**Removing redundant entries:** If a mist contains several identical entries, with the same color, shape, and sign, then redundant entries can be deleted so long as the ratios of distinct entries remain the same.

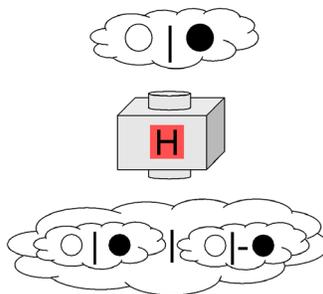


**Dropping mist for single entry:** If there is only one entry in the mist, then the mist can be dropped. For example:

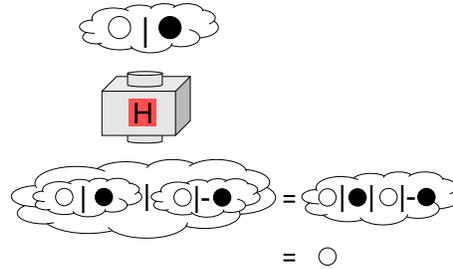


## Passing mist through gates:

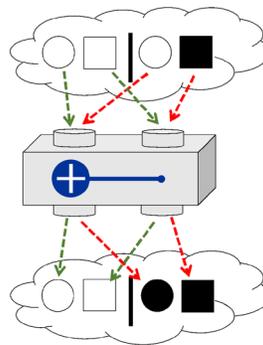
Each qubit that enters the mist is replaced by the qubit pair that results from passing through the H gate. For example, the white qubit when passing through H gate transforms into a white, positive black mist combination and the black qubit transforms into the white, negative black mist combination, as seen in the example above.



If we then follow the mist rules, then we remove the inner mist and then we *cancel entries* and *remove redundant entries*. Finishing with the output of one bit in 0 state

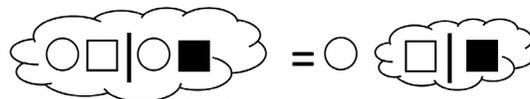


If a two-qubit mist is input into a two-qubit gate, the output can be obtained by separately passing each entry in the mist through the two-qubit gate. The shapes in each entry should be inserted into the input ports in the same order that they appear in the entry: the left shape (circle) is inserted into the left port, the right shape (square) into the right port. In this example involving the CNOT gate, quantum entanglement is created, because while the input mist can be factorized according to the mist rules, the same is not true of the output. Quantum entanglement refers precisely to this inability to factorize states.



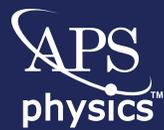
### Additional mist rules (less frequently used)

**Factorizing mist:** If the first few shapes in every entry have the same sequence of colors, then these shapes can be factored out of the mist on the left. Similarly, if the last few shapes in every entry have the same color sequence, these shapes can be factored out to the right. This is similar to factoring out a in an expression such as  $ax + ay = a(x + y)$ . For example:



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