PhysicsQuest 2025: Tangled

| **Title:** Tangled  **Subtitle:** Entangled vs Product States  Developed by - Zachary Simmons, Ph.D, Malcolm Johnson - Milwaukee School of Engineering | | |
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| **Total Time:** 30 min  **Audience:** Middle School Science Teachers  **Education Level:** Grades 5 - 9 | | |
| **Content Area: Quantum Physics**  **Educational topic: Superposition, Entanglement,**  **Objectives: SWBAT:**   * Define superposition qualitatively using the spinning coin analogy * Explain entanglement qualitatively and distinguish an entangled state from a non-entangled (product) state * Know that entanglement can occur over arbitrary distance * Identify and avoid common misconceptions and hype regarding entanglement   **Key Question:**  How do we define entanglement and superposition in the context of a quantum computer? | | |
| [**QIS Key Concepts**](https://q12education.org/wp-content/uploads/2023/12/MS-QIS-Key-Concepts-FINAL-12-7-2023.pdf)**:**  **MS Science 2.1: Quantum States**   * Students will be able to explain that the state of a system defines its properties and can be used to make predictions about its behavior, including the outcomes of measurements and experiments. * Students will be able to explain that quantum states may have indefinite (probabilistic) outcomes, meaning that the outcomes are not determined until they are measured, if they are in a superposition of different possibilities.   **MS Science 3.2: Quantum Measurements**   * Students will demonstrate how measuring a property of a system can change the state of the system.   **MS Science 5.1 Entanglement -** When two systems are entangled with each other; the properties of the second qubit cannot be described | | |
| **Materials** | * Plastic coins * Game boards (teacher must photocopy for each student - original found in kit) * Printed scorecards (teacher must photocopy for each student - original found in kit) | |
| **Overview:** This activity is designed as an engaging game with the goal of developing student intuition about some of the most basic terms in quantum physics and quantum computing, in particular *superposition* and *entanglement*. Quantum technology is ever more relevant in our world and “quantum-“ things appear frequently in society and science fiction. It is more important than ever that students have opportunities to learn about these ideas in a way that connects to actual science.  This activity is a game that uses a spinning coin as an analogy for a qubit (a quantum bit used in quantum computers). When students set a single coin spinning, they can see that it is not heads or tails but both; this is an analogy for superposition. Classical bits can only be a 0 or 1, while qubits are in superposition of states until they are observed. Students can also see that the coins do not spin indefinitely, they are fragile, susceptible to slowing down and being disrupted, not unlike a qubit being susceptible to decoherence. Students can also appreciate that while the spinning coin is in a sense “both” heads and tails, when stopped (“measured” by being slapped down on the table), the coin ends up only either heads or tails. Also, the outcome is random.  More interesting gameplay occurs when another coin is introduced. Students play against each other with their coins simulating either non-entangled (product) or entangled states. The students choose to play for either heads or tails, i.e. they score when their chosen side turns up. Students score points based on both the skill of how accurately they spin their coin to a designated region of the game board as well as the result of measurement of their qubit and whether what they get matches the side they are playing for. Students can clearly see a difference in behavior between product and entangled states in the game mechanics. In the product state, “measurements” for both players are independent. In the entangled state, “measurements” are linked when the first is measured, the value of the other player’s coin is fixed by that first measurement. | | |
| **Teacher Background:**  It is predicted that quantum computing will be able to solve some problems that are intractable with “classical” computers. One of the problems that gets the most attention is encryption; quantum computers, as they become more capable, may be able to crack current encryption methods. As a result, there is tremendous interest in this computing approach and the principles that underlie it. However, there’s also a lot of hype and exaggeration around anything “quantum;” see depictions in movies and pop culture. This lesson seeks to help build student understanding about some foundational quantum concepts: superposition and entanglement. For students at this level, it’s appropriate to describe quantum mechanics as the science that describes what happens when things are very small (think atoms). Quantum mechanics can have some remarkable consequences, and it is hard for us to visualize and relate since we only have experience with things that are very large by comparison.  **Mathematical explanation - not required to understand the concepts:** Quantum computers use qubits rather than bits (1’s and 0’s). What is a qubit? A qubit is a system that can be in a mathematical superposition of two different states at the same time. In this activity we are using a spinning coin to convey the idea, so let us think of the 1 and 0 as heads H and tails T of a coin. A superposition state can be written in many different ways/with different notation systems. A simplified example of a particular state looks like this: , where we have used the Greek letter Psi to represent the state and H and T to represent heads and tails, and there is a coefficient of in front of each possibility. This state would be a superposition that is half H and half T, although being "in superposition" in general does not require it be 50% H and 50% T. Mathematically, the exact probability of each outcome is calculated by squaring each coefficient, so the ‘s becomes ’s in our example .  In a real quantum computer, qubits are implemented using many different physical systems such as electron spins (up vs. down) or energy states of an atom or ion, or the direction in tiny superconducting current loops. In this lesson, a spinning coin is our analogy for this. Measurement destroys the superposition and yields an outcome probabilistically. In our particular example, it converts the spinning coin superposition into either heads or tails with equal likelihood.  Entanglement can occur when there are multiple qubits. Classically this isn’t possible i.e. multiple simultaneous real coin flips do not impact each other but are independent and their probabilities are given by a product. Let's consider the classical case first. Starting with two coins, each in a superposition: , and . If you were to multiply the two states together, you'd get: , where the first H or T in each term represents the first coin and the second the second coin. If you were to then measure the first coin and for example get 'H', i.e. this would change the product to . (Note: technically, you would then adjust the coefficients so the probabilities still add up to 1 ). Notice if you then measured the second, you are still equally likely to get H or T for the second coin. In other words, measuring one coin does not affect the possible outcomes for the second. This is what happens in a classical (product) state. Mathematically, you could take the state and factor it into the original and .  In contrast, consider this state . You cannot factor this state into a product of two. If you were to measure the first qubit for this configuration, and for example get 'H', the state would then be ( after adjusting the coefficient). You immediately know the second qubit must be an H as well! Measuring the first coin impacts what is possible for the second. This is an example of an entangled state. This particular kind of entangled state is called a Bell state and we'll identify it with a unique symbol, capital Phi, . Another Bell state is . Notice in this case, if you measure the first as H, the second must be T. This distinction where measuring one coin (qubit) does not affect the other in the product state, while it does in the entangled state, is the main point the game attempts to convey.  The fact qubits have these properties where they can be in superposition and entangled with each other is part of what allows the exceptional capabilities of quantum computers compared to “classical” computers. For students at this level, they don’t necessarily need to see *product* vs *not able to be written as a product* as the distinction that makes entangled states special. Instead, the focus is on the simple point that in a product state (perhaps non-entangled state would be better terminology), measurements are independent. One coin does not affect the other. In the entangled state however, measuring one impacts the other. No math or factoring is required for students to see this. They can see this difference in behavior in the game.  Something that is remarkable about this behavior for entanglement is that it appears to work instantly over arbitrary distance. In other words, you can make entangled qubits very far apart and measuring one will still immediately impact the second. This is strange because we know nothing can travel faster than light. Building on this, one very common misconception spread about entanglement is that it may be a way to send *signals* faster than the speed of light. While it is true that the entanglement will operate immediately over arbitrary distance, it can’t be used to send a signal because the outcome of measurement is probabilistic; you can’t choose the outcome of one and so fix the entangled partner. These points can be made to students by separating game boards and explaining you could still play while infinitely far apart, but noting that the result of measurement is random and so can’t be used to send messages. | | |
| **Key Terms (used or presented after the activities - see Foreward for details)**  **Superposition:** an object that can be in more than one state at a time.  **Measurement:**  asking of the coin, forcing the issue, which are you: heads or tails? **Measurement destroys the superposition.**  **Decoherence:** inadvertent measurement. Quantum states are very fragile and so if they are disturbed, they will land on one state or the other. This tendency is represented naturally in the activity by the fact that the coin does not spin forever but will slow and land on heads or tails regardless of whether a player chooses to measure it.  **Entanglement:** a relationship between different objects (let's limit our discussion to two objects) that links them together. If one object of a perfectly entangled pair is in a particular state, then you would know immediately what state the other object is in. Note: entanglement doesn't allow setting the particular state of an object, measurement is probabilistic, but does dictate the relationship between objects.  **Bell states:** the names of the two maximally entangled states. **Teacher Tips:**  1. Suggested [STEP UP Everyday Actions](https://engage.aps.org/stepup/curriculum/everyday) to incorporate into activity    1. When pairing students, try to have male/female partners and invite female students to share their ideas first    2. As you put students into groups, consider having female or minority students take the leadership role.    3. Take note of female participation. If they seem to be taking direction and following along, elevate their voice by asking them a question about their experiment. 2. Consider using white boards so students have time to work through their ideas and brainstorms before saying them out loud. 3. As students experiment, roam around the room to listen in on discussion and notice experiment techniques. If needed, stop the class and call over to a certain group that has hit on an important concept. 4. Consider [culturally responsive tools and strategies](https://www.nciea.org/blog/a-culturally-responsive-classroom-assessment-framework/) and/or [open ended reflection questions](https://www.cde.state.co.us/standardsandinstruction/es-student-reflections-mc) to help push student thinking, have students track their thinking during the activity, connect to their lives, and create opportunities to develop STEM identity. 5. Allow the work of physicists to come alive by signing up for a virtual visit from a working physicist using [APS’s Physicist To-Go](https://www.aps.org/initiatives/physics-education/k-12/physicists-to-go) program. You can request a plasma scientist to talk about the concepts students learned in this activity! | | |
| **Teacher’s Guide** | | |
| **Objectives:**  – \*SWBAT   * Define superposition qualitatively using the spinning coin analogy * Explain entanglement qualitatively and distinguish an entangled state from a non-entangled (product) state * Know that superposition and entanglement are fragile * Know that entanglement can occur over arbitrary distance * Identify and avoid common misconceptions and hype regarding entanglement   “Quantum” ideas are frequently invoked in movies and television, often giving a fantastical impression. If students come away from this activity with broad ideas like quantum processes are fragile, building a computer using such processes is very difficult, and the capabilities of a quantum computer are perhaps more modest than depicted but still very interesting; that would be a great outcome.  \*It is important to understand that student goals may be different and unique from the lesson goals. We recommend leaving room for students to set their own goals for each activity. | | |
| **Before the Experiment:** | | 1. Read background 2. We invite you to watch a [brief video demonstration](https://www.youtube.com/watch?v=o_Mhr-0xF0U&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=5) of the developer conducting the experiment you’ll be facilitating with your students. 3. Consider exploring XXX’s narrative using the lessons ideas detailed on the Introduction found in your materials kits. 4. Print and collect materials 5. Mark poker chips with 1 and 0 or other clear way of distinguishing 6. Organize students into pairs, each pair gets 2 coins, boards, score sheets |
| **Setting Up** | | 1. [Print](https://drive.google.com/file/d/1DmCvyv1IF3uLwC171TKmo1vkptS5hR6v/view?usp=sharing) one gameboard and one score sheet per student. Distribute materials 2. Discuss background and game rules 3. Review the different “games states (number 2 below)” with students and make sure they choose a game state for each round.   Tangle: Game Rules and Directions  You will use a spinning coin to represent a qubit in superposition in this game. Two students each with a coin play against each other to explore the difference between entangled qubits and non-entangled qubits.  Before starting, familiarize yourself with the game board and score sheet. Try slapping (“measuring”) and clapping (stopping) your coin. Observe the randomness of your measurements.   1. Fill out the top of your score card and choose the side that you are playing for, either heads H (1) or tails T (0). This determines what side of the coin you will score points from. Notes: Since the sides are equally likely, there is no advantage to H or T. Also, a player picking one side does not mean the other player cannot pick the same side. Picking the same side does not mean players get the same score. 2. For each round choose a game state:   a. non-entangled,  b. entangled state 1: (must match) , or  c. entangled state 2: (must anti-match) .  It is recommended you play each state once per game. Mark the game state you are currently playing on the score card   1. For each attempt (tangle) in a round,    1. Both players spin their coins (like tops) toward the center of their individual game board, from outside its edge. If the coin falls over or goes off the game board etc., immediately pick it up and keep trying to spin it into the middle.    2. The player with the first coin to reach the middle of their board slaps their coin down, “measuring” it.       1. If in the non-entangled game state, the second player then immediately slaps their coin down, “measuring” theirs as well.       2. If in either of the entangled states, the second player “claps” their coin between their hands, stopping it from spinning.          1. If in the entangled state 1: , they flip their coin so that it matches player one’s coin.          2. If in the entangled state 2: , they flip their coin so that it is the opposite of player one’s coin.    3. Tangle scoring       1. The player who first got to the middle, gets one skill point. Skill points have no scientific meaning and are just for fun and can be taken out if desired.       2. If that player’s measured coin matches their chosen side for the round, they get a state point       3. The second player gets no skill point, but if their coin matches their chosen side for the round, they get one state point 2. Repeat step 3 as many times as necessary to complete the round. There are by default 11 attempts (tangles) per round. At the end of the round, the skill and state points are added, giving a round score. The score has not scientific meaning, and is just for the fun of the game. 3. Repeat steps 2-4 for each game round. The player who wins more rounds wins the game. Note: there are by default 3 rounds per game, with the game state switched each round (recommended) to encourage players to try each game state. 4. Extension: entanglement over arbitrary distance shown by game board separation. Interestingly, entanglement can occur over arbitrary distance. This can be emphasized to students by separating the game boards farther and farther apart while playing, providing a fun twist.   Game Board:    Scoresheets:  **Round 1**   | Player Names | | | Game State | | | | | | | Score on Heads or Tails? | | | | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | -  - | | | * Non-entangled * Entangled State 1 – Must Match * Entangled State 2 – Must Anti-Match | | | | | | | A black background with a black square  Description automatically generated with medium confidence | | | | | Tangle | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 10 | 11 | Total | | State Point |  |  |  |  |  |  |  |  |  | |  |  |  | | Skill Point |  |  |  |  |  |  |  |  |  | |  |  |  |   **Round 2**   | Player Names | | | Game State | | | | | | | Score on Heads or Tails? | | | | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | -  - | | | * Non-entangled * Entangled State 1 – Must Match * Entangled State 2 – Must Anti-Match | | | | | | | A black background with a black square  Description automatically generated with medium confidence | | | | | Tangle | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 10 | 11 | Total | | State Point |  |  |  |  |  |  |  |  |  | |  |  |  | | Skill Point |  |  |  |  |  |  |  |  |  | |  |  |  |   **Round 3**   | Player Names | | | Game State | | | | | | | Score on Heads or Tails? | | | | | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | --- | | -  - | | | * Non-entangled * Entangled State 1 – Must Match * Entangled State 2 – Must Anti-Match | | | | | | | A black background with a black square  Description automatically generated with medium confidence | | | | | Tangle | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | | 10 | 11 | Total | | State Point |  |  |  |  |  |  |  |  |  | |  |  |  | | Skill Point |  |  |  |  |  |  |  |  |  | |  |  |  | |
| **During the Experiment** | | **-Collecting Data**  Fill out the score sheet according to the game rules above as students play |
| **Conclusion** | | The students have their filled-out score sheets. This leads to some interesting questions to put to students:   1. Looking at the “state” rows for your entire game, was there any trend or did it look random? If you were to play many times, what do you think would happen to the number of heads and tails? [Teacher helps students build intuition about probability: 50/50 with many plays.] 2. What do you notice about the state rows for both players for the product state round and the entangled state rounds? [Teacher helps students see that product states are not correlated, while entangled states either match or are flipped.] 3. Does the state that you’re playing for matter? Does it matter if you play for heads vs tails? 4. You played over some distance, simulating entanglement and may have moved game boards apart to emphasize it works even when far apart. Do you know how far apart entanglement works in the real world? [Note: this is an opportunity for teacher to note entanglement works even when arbitrarily far apart. This provides a springboard to an extension discussion of the speed of light and how although entanglement apparently works over arbitrary distance instantly, you cannot use it to e.g. send messages faster than light (superluminal communication) because the outcome of measurement is random. Using entanglement to send messages is a very common point in science fiction.] |
| **Student’s Guide** | | |
| **Intro:**  The purpose of this game is to help you learn some of the fundamental terms in quantum computing. Quantum computers are a new kind of computer that may be able to do things that are currently impossible with even the most powerful “regular” supercomputer. To do this they use quantum mechanics, the science of how things work when they are very small. Quantum mechanics shows up in movies and TV all the time but often is presented in misleading ways. This game will teach you about two quantum mechanical ideas: superposition and entanglement.  While regular computers use bits- 0’s or 1’s stored in the computer, quantum computers use qubits. Qubits have a special ability- they can be in a **superposition**. A superposition is a combination of two different states at the same time. This can happen in quantum mechanics. In a real quantum computer, this might be done with electrons or atoms acting as qubits. We will explore an analogy- and use a spinning coin to represent a qubit. The spinning coin has heads H (which could represent 1) on one side and tails T (which could represent 0) on the other. When it’s spinning, notice it’s not H or T but both; this is like a qubit in superposition. If you stop the coin however, “measure” it by slapping it on the table, it will no longer be in a superposition but be either H or T. If you did this many times, you would see that its random which side faces up. Notice also that a coin doesn’t spin forever but will stop on its own. This is like how a real qubit behaves. Real qubits can be in a superposition of states and when measured can only be in one state at a time. Real qubits also tend to “fall over,” the superposition breaks down; this is called decoherence.  The other important idea is called **entanglement**. Entanglement can happen between two qubits. It can be explained with math, but we can also see its consequences. If qubits are entangled, measuring one will impact the state of the other one. This is very strange. In our coin analogy (but now with two “entangled” coins) this would mean that if you slapped one coin and got H, the 2nd coin would match, also be H (for one kind of entanglement). A non-entangled state would not have this matching behavior. If you measure one coin in a non-entangled pair it would have no impact on the second. They would be independent and both would be random.  You will observe both of these ideas in the game tangle. | | |
| **Objective:**  Win the game.  Observe a spinning coin as an analogy for superposition.  Learn about the difference in behavior between “entangled” and “non-entangled” coins.  Room for student driven objectives too: After reading the introduction, what is your essential question or objective for this activity? | | |
| **Before the Experiment** | | 1. Make sure you have the materials: game rules, scoresheets, gameboards and coins. 2. Make sure you’ve read the directions and looked at the game board and scoresheets. |
| **Setting Up** | | It may be a good idea to warm up a bit on your own, try spinning your coin toward the center of the board, practice slapping (“measuring”) and clapping your coin. Observe and get a feel for how measurement results are random. Pair up with a partner, lay out your game boards and score sheets, |
| **During the Experiment** | | **-Collecting Data**  Tangle: Game Rules and Directions  You will use a spinning coin to represent a qubit in superposition in this game. Two students each with a coin play against each other to explore the difference between entangled qubits and non-entangled qubits.  Before starting, familiarize yourself with the game board and score sheet. Try slapping (“measuring”) and clapping (stopping) your coin. Observe the randomness of your measurements.   1. Fill out the top of your score card and choose the side that you are playing for, either heads H (1) or tails T (0). This determines what side of the coin you will score points from. Notes: Since the sides are equally likely, there is no advantage to H or T. Also, a player picking one side does not mean the other player cannot pick the same side. Picking the same side does not mean players get the same score. 2. For each round choose a game state: either non-entangled, entangled state 1: (must match) , or entangled state 2: (must anti-match) . It is recommended you do one of each game state per game, at least to start. Mark the game state you are using for each round on your score card. 3. For each attempt (tangle) in a round,    1. Both players spin their coins (like tops) toward the center of their individual game board, from outside its edge. If the coin falls over or goes off the game board etc., immediately pick it up and keep trying to spin it into the middle.    2. The player with the first coin to reach the middle of their board slaps their coin down, “measuring” it.       1. If in the product (non-entangled) game state, the second player then immediately slaps their coin down, “measuring” theirs as well.       2. If in either of the entangled states, the second player “claps” their coin between their hands, stopping it from spinning.          1. If in the entangled state 1: , they flip their coin so that it matches player one’s coin.          2. If in the entangled state 2: , they flip their coin so that it is the opposite of player one’s coin.    3. Tangle scoring-       1. The player who first got to the middle, gets one skill point       2. If that player’s measured coin matches their chosen side for the round, they get a state point       3. The second player gets no skill point, but if their coin matches their chosen side for the round, they get one state point 4. Repeat step 3 as many times as necessary to complete the round. There are by default 11 attempts (tangles) per round. At the end of the round, the skill and state points are added, giving a round score. 5. Repeat steps 2-4 for each game round. The player who wins more rounds wins the game. Note: there are by default 3 rounds per game, with the game state switched each round (recommended) to encourage players to try each game state. 6. Extension: entanglement over arbitrary distance shown by game board separation. Interestingly, entanglement can occur over arbitrary distance. This can be emphasized to students by separating the game boards farther and farther apart while playing, providing a fun twist.   **-Analyzing Data**  Whoever wins more rounds wins. |
| **Conclusion** | | * + - 1. What do you notice about the relationships between the state rows between player scorecards for product vs entangled rounds?       2. Did the game state rows matter in the game? What do you think would happen if you played many tangles?       3. Did your choice of H or T matter in the game? What do you think would happen if you played many rounds?       4. Based on your observations from this game, define “superposition” and “entanglement” in your own words. Use evidence from this activity to support your definition.       5. Was your personal essential question answered? If so, what is the answer? If not, what additional information would you need to answer it? |
| **Additional Resources:**   * Introduction to Classical and Quantum Computing by Wong   https://www.thomaswong.net/introduction-to-classical-and-quantum-computing-1e4p.pdf   * Quantum Computing for the Quantum Curious by Hughes et.al. https://library.oapen.org/handle/20.500.12657/48236 | | |
| **Assessment/Extension activities\*\* (optional to extend thinking after the lesson):**   * Real world connections –   + Sign up for [Physicists To-Go](https://www.aps.org/programs/outreach/physiciststogo.cfm) to have a scientist talk to your students. * Suggestions for drawing, illustrating, presenting content in creative ways * Engineering and design challenges connected to the content   + if engineering challenges have a time constraint, students are allowed to keep iterating and developing their ideas outside of class time and continue to participate in the challenge at a later date   \*\*Real world situations/connections can be used as is, or changed to better fit a student’s own community and cultural context. | | |