PhysicsQuest [2025]: Entangled & Shuffled

| **Title:** Entangled & Shuffled  **Subtitle:** Exploring quantum correlations and entanglement through tabletop games  Developed by - Danyel Cavazos - University of Chicago | | | |
| --- | --- | --- | --- |
| **Total Time:** 30-45 minutes  **Audience:** Middle School Science Teachers  **Education Level:** Grades 5 - 9 | | | |
| **Content Area:** Quantum Information Science  **Educational topic:** Quantum Correlations, Superposition, Entanglement  **Objectives:**   * Students will play a few games that will allow them to make connections between regular items like playing cards and the behavior of quantum particles. * Some of the features of the game will highlight the differences between regular, everyday systems and quantum technologies.   **Key Question:**   * What makes quantum particles and systems different from normal objects? | | | |
| [**Next Generation Science Standards**](https://www.nextgenscience.org/sites/default/files/MSDCI.pdf)**:**  HS-PS4-5 Waves and their Applications in Technologies for Information Transfer   * Communicate technical information about how some technological devices use the principles of wave behavior and wave interactions with matter to transmit and capture information and energy. * PS4.A: Wave Properties. Information can be digitized (e.g., a picture stored as the values of an array of pixels); in this form, it can be stored reliably in computer memory and sent over long distances as a series of wave pulses. * PS4.C: Information Technologies and Instrumentation Multiple technologies based on the understanding of waves and their interactions with matter are part of everyday experiences in the modern world (e.g., medical imaging, communications, scanners) and in scientific research. They are essential tools for producing, transmitting, and capturing signals and for storing and interpreting the information contained in them.   Connections to Engineering, Technology, and Applications of Science:   * Interdependence of Science, Engineering, and Technology: Science and engineering complement each other in the cycle known as research and development (R&D). * Influence of Engineering, Technology, and Science on Society and the Natural World: Modern civilization depends on major technological systems. * Communicate technical information or ideas (e.g. about phenomena and/or the process of development and the design and performance of a proposed process or system) in multiple formats (including orally, graphically, textually, and mathematically). | | | |
| **Materials** | **Provided in kit**   * Deck of playing cards * Pen/pencil and paper * S index calculating boards (in sheet protectors)   **Teacher provided:**   * Dry erase markers * Dry erase marker eraser liquid | | |
| **Overview:** Students will model superposition, correlations, and entanglement of particles using playing cards. This will help students visualize and understand basic properties of quantum information science | | | |
| **Teacher Background:**  **What is Quantum Information Science (QIS)?**  The field of Quantum Information Science (QIS) is a multidisciplinary area of research that is positioned right in between science, engineering and technology. It studies how we can take advantage of the unique properties of quantum systems for technological and information applications such as creating new and better computers, developing digital networks with better encryption protocols, and creating sensors and measuring devices with enhanced precision.  **Why is QIS important?**  During the last century, the development of lasers and transistors led to an explosion in the availability of technology and information circulating around the world. This has strongly reshaped our societies, defining a new “information age”. Effectively, all the information and data that we use is currently stored, transmitted and processed through standard ("classical") methods that involve the manipulation of electronic states that are interpreted as “ON” or “OFF”, "0" or "1" states of information known as bits.  The complexity of these information systems is not a feature of the fundamental parts of our computers, but rather only a result of the enormous scale of both the number and speed at which bits are processed in our devices. A significant challenge, however, relies on the fact that the amount of memory and processing power required to handle and analyze large systems scales exponentially. This means that as our information systems keep expanding, the amount of resources will become unsustainable in the long term. The motivation behind this interest in QIS is the potential that quantum technologies have in providing us with a way forward to navigate this problem.  **What distinguishes quantum technologies from regular devices?**  We can identify three “ingredients” that distinguish quantum technologies from regular devices:  1) **Superposition**: while a bit can have a value either 0 or 1, a quantum bit (qubit) can have a value that is either 0, 1 or a quantum superposition of these values. In a state of superposition, the value of the qubit cannot be described as either 0 or 1 in a definite way. Given two bits, a regular computer can store four possible different values (00, 01, 10, or 11), although only one of those at a time. Given two qubits, in principle all the four values can be represented simultaneously. Mathematically, we represent this as:  |⟩=a|00⟩+ b|01⟩+c|10⟩+d|11⟩  Each bracket |⟩ (“ket” for short) represents a state on which the system can be, and the fact that they are added together indicates the superposition.  2) **Correlations**: the state of a qubit can be readily affected by its interaction with other elements in the system, influencing the probability of a certain outcome during experiments. Given the right circumstances, a particular combination of states might prevent certain outcomes through destructive quantum interference.  3) **Entanglement**: when qubits become entangled, they form a “global” system such that the quantum state of different parts of the system cannot be described independently. We thus say that there exist specific correlations between each of the components.  A key insight to understand the advantages of quantum systems consists in realizing the similarity between the superposition of quantum states (|00⟩+ |01⟩+ |10⟩+… ) and the way a classical parallel computer runs, where many different inputs are processed within the time of a single calculating cycle. However, unlike the stack of CPUs that is necessary to run a classical parallel computation, a single quantum system has the potential to provide parallel processing as a “built-in” feature. Initially, this suggests the possibility of carrying out these calculations with a much smaller number of resources and a method to bypass the exponential explosion problem.  **How can we use tabletop games to explain QIS?**  Given that studying quantum systems is both technically and conceptually challenging, QIS topics and concepts are usually discussed until students take advanced undergraduate and graduate level classes. However, it is possible to highlight the key differences between classical and quantum systems by using items commonly found in tabletop games such as cards. We think the fact that these items are easily accessible should help to make the quantum concepts more relatable to young students and a general audience. | | | |
| **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:**  – \*Students will play a few games that will allow them to make connections between regular items like playing cards and the behavior of quantum particles.   * Some of the features of the game will highlight the differences between regular, everyday systems and quantum technologies.   \*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. We invite you to watch a [brief video demonstration](https://www.youtube.com/watch?v=GiZQV5vTu5E&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=11&t=13s) of the developer conducting the experiment you’ll be facilitating with your students. 2. Consider exploring XXX’s narrative using the lessons ideas detailed on the Introduction found in your materials kits. 3. Prepare a few decks of cards that are randomly shuffled 4. Prepare a few decks of cards that are arranged in a specific color pattern (ex. all red, all black, alternating colors, 2 blacks then 2 reds, etc.) 5. Ask students what they think it means for particles to be “entangled”. Let them know this is a new concept they probably haven’t learned about so their ideas are all just brainstorms. | |
| **Setting Up** | | 1. Pass out part of a normal, randomized deck (Labeled deck 1) of cards to each student group. 2. Pass out part of a prepared deck (Labeled deck 2) to each student group. 3. Give each student group a [copy](https://drive.google.com/file/d/1hwzDXkOS6ecOAOCIrxzklcQoxNkPdtam/view?usp=sharing) of the S - index worksheet (for part 2) | |
| **During the Experiment** | | **-Collecting Data**  **Part 1:**   1. Introduce the mathematical idea of a correlation index, that is a number that has a meaning depending on the outcomes of the events:   **+1** if the colors of the cards match (ex. red-red or black-black)  A close up of a card  Description automatically generated  **-1** if the colors of the cards don’t match (red-black)  A close up of a card  Description automatically generated     1. Hand out shuffled, randomized decks to each group. Ask students to divide the cards into two parts. 2. The students will now start drawing pairs cards, one from each of the decks. Ask them to compare their colors and to evaluate and write down the correlation index for each case. 3. Have them record their observations for deck 1 and deck 2 in their notebooks. 4. Discuss with the students what kind of pattern did they observe.   There should be no correlations between them and there is no way to predict what the outcome will be. **This is an uncorrelated system**.  Now repeat exercise, but instead hand out the decks that you pre-arranged in some patterns. Now the outcomes are predictable. **This is a correlated system**.  Part 2:  **Online Version**   1. There is an online version of this section of the activity that can be found [here](https://quantumlab-uchicago.github.io/TeachingDemos/BellGame.html).   **Hands-on version**   1. Hand each team part of a prepared, patterned deck of cards. 2. Each group draws four cards from the shuffled deck and lays them on the board 3. Ask them to start flipping the cards in pair and calculating the correlation indexes according to the rule:   Same color = **+1** Different color = **-1**   1. Add the four different correlation indexes using the pattern C1 + C2 – C3 + C4 as indicated on the board. 2. Take the absolute value of the outcome. We will refer to the result as the “S index”.   Example  Initial draw:  A diagram of a diagram  Description automatically generated  First pair: red and black, so C1 = -1  A diagram of a card game  Description automatically generated  Second pair: red and red, so C2 = +1  A card game with different colored squares  Description automatically generated with medium confidence  Third pair: red and black, so C3 = -1  Fourth pair: red and red, s o C4 = +1  Final evaluation: S = |C1 + C2 – C3+C4| = 2  A card game with a diagram  Description automatically generated with medium confidence   1. Ask each group to share their results. They should all get the result S= 2.   **NOTE:** sometimes students get a different value than 2, but that is due to a calculation error. If that happens, check each of the correlation values. The most common mistake is not to add the four correlation values appropriately (C3 should be subtracted).   1. Play a few different rounds to motivate the idea that the result is always 2. 2. Present challenge to the students: if you hand-pick cards instead of shuffling them, is it possible to get an outcome value larger than 2? | |
| **Conclusion** | | Ask the students to argue whether they think that it is possible/not possible to get an S value larger than 2. After some discussion, it should become clear that even when hand-picking, it is **NOT** possible to get a value larger than 2. This exemplifies the concept of Bell’s inequality.  For everyday systems, there is a limit that sets a maximum value for correlation indexes. In our case the inequality is S ≤ 2.  Discuss with the students that the reason for this is that the outcome depends on the colors of the four cards, and their different correlations. Even when the cards are facing down, it is either black or red (similar to a regular computer bit), so once three out of the four cards have been drawn, you immediately know the outcome of the fourth correlation.  This is related to the concept of “reality” in quantum mechanics. In classical systems they *really* are only on one state or another. That is not the case for quantum systems  The fact that the situation is presented as a challenge is very engaging for students, and it also shows that there seems to be a “limit” in the maximum correlations that we can get, even after hand-picking the cards. In a few words, it looks like it is impossible to get a value larger than 2.  When the same exercise is carried out using entangled quantum particles such as photons (particles of light) or single atoms at very low temperatures, it is possible to get values of S>2, and thus surpass Bell’s inequality. In a way, this kind of test can be used to verify if a system is having quantum effects or not. Ask the students to imagine ways on which this could be possible.  Relate this to the idea that if we had “quantum cards”, then we couldn’t properly describe them as being either black or red before looking at them. Pictorially, we can imagine them as constantly fluctuating between being red or black, and we would have to represent them with a video or an animation instead of a picture. In this case, even after revealing 3 out of the 4 cards, it wouldn’t be possible to predict the value of the last correlation. Or, in other words, when carrying out the game with “quantum cards”, the color of the last card can flip at the last minute regardless of the previous outcomes. These extra possibilities result in the value of S surpassing the classical limit.  Finally, put all the ideas together to relate this example to how quantum technologies work. In the cards game, we saw that when playing under the regular rules, there is no way to obtain a value of S > 2. This is due to the cards being definitely either black or red. Similarly, regular computers work with classical bits, which are also definitely either 0 or 1. This imposes limits on the capabilities of the computers.  One way in which we can imagine surpassing that limit in the card game is having cards that are not either black or red in a definite way. Similarly, quantum computers work using qubits, and because they can be in a superposition state, they don’t necessarily have a definite state. These additional possibilities allow them to surpass some of the limitations of regular computers. | |
| **Student’s Guide** | | | |
| **Intro: What is Quantum Information Science (QIS)?**  The field of Quantum Information Science (QIS) is a multidisciplinary area of research that is positioned right in between science, engineering and technology. It studies how we can take advantage of the unique properties of quantum systems for technological and information applications such as creating new and better computers, developing digital networks with better encryption protocols, and creating sensors and measuring devices with enhanced precision.  **Why is QIS important?**  During the last century, the development of lasers and transistors led to an explosion in the availability of technology and information circulating around the world. This has strongly reshaped our societies, defining a new “information age”. Effectively, all the information and data that we use is currently stored, transmitted and processed through standard ("classical") methods that involve the manipulation of electronic states that are interpreted as “ON” or “OFF”, "0" or "1" states of information known as bits.  The complexity of these information systems is not a feature of the fundamental parts of our computers, but rather only a result of the enormous scale of both the number and speed at which bits are processed in our devices. A significant challenge, however, relies on the fact that the amount of memory and processing power required to handle and analyze large systems scales exponentially. This means that as our information systems keep expanding, the amount of resources will become unsustainable in the long term. The motivation behind this interest in QIS is the potential that quantum technologies have in providing us with a way forward to navigate this problem. | | | |
| **Objective:**   * \*Students will play a few games that will allow them to make connections between regular items like playing cards and the behavior of quantum particles. * Some of the features of the game will highlight the differences between regular, everyday systems and quantum technologies. * After reading the introduction, what is your essential question or objective for this activity? | | | |
| **Before the Experiment** | | 1. What do you think it means for particles to be “entangled” on a quantum scale? This is a new concept you probably haven’t heard much about, so all ideas are good ones! | |
| **Setting Up** | | 1. Get two portions of a deck of cards from your teacher (Deck 1 and Deck 2) 2. Get an [S - index board](https://drive.google.com/file/d/1hwzDXkOS6ecOAOCIrxzklcQoxNkPdtam/view?usp=sharing) and dry erase markers (if laminated) or pen (if printed) | |
| **During the Experiment** | | **-Collecting Data**  **Part 1**   1. Split deck 1 into two parts. Take the first card from each side and turn face up. Observe the numbers, colors of each card. 2. Continue flipping the top card face - up, observe. 3. Do you see any patterns in the pair of cards with regards to color, number, etc. 4. Record your observations in your notebook. 5. Repeat steps 1-4 with Deck 2. You can use a table like the one below if you’d like  | Deck # | Card 1 | Card 2 | Observations (patterns, colors, numbers, etc.) | | --- | --- | --- | --- | |  |  |  |  | |  |  |  |  | |  |  |  |  |  1. Discuss your findings with your classmates and the teacher.   Part 2:  **Online Version**   1. There is an online version of this section of the activity that can be found [here](https://quantumlab-uchicago.github.io/TeachingDemos/BellGame.html).   **Hands-on Version**   1. Get a deck (or portion of a deck) of shuffled cards. 2. Draw four cards from the shuffled deck and lay them on the board 3. Calculate the correlation indexes according to the rule:   Same color = **+1** Different color = **-1**   1. Add the four different correlation indexes using the pattern **C1 + C2 – C3 + C4** as indicated on the board. 2. Take the absolute value of the outcome. We will refer to the result as the “S index”. 3. share their results. They should all get the result S= 2.   **NOTE:** sometimes students get a different value than 2, but that is due to a calculation error. If that happens, check each of the correlation values. The most common mistake is not to add the four correlation values appropriately (C3 should be subtracted).   1. Play a few different rounds to motivate the idea that the result is always 2. 2. Try hand-pick cards instead of shuffling them, is it possible to get an outcome value larger than 2? | |
| **Conclusion** | | Answer these questions to the best of your ability using what you learned today during this activity and the information in the introduction. Discuss the answers with your class and teacher.   1. What does it mean for two particles to be correlated? Use evidence from this experiment to support your definition. 2. Before the card is turned over, what color is it? Use this answer to help you define the word superposition. 3. What happens to the value of S in the card game when playing under the regular rules, and why can’t it be larger than 2? 4. How does the concept of “quantum cards” differ from regular cards in the game? Why might this allow for a value of S greater than 2? 5. How is the card game related to quantum computers and classical computers? Explain how qubits in quantum computers can surpass the limitations of classical bits. 6. 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:**   * The [Quantum Atlas](https://quantumatlas.umd.edu/entry-list/) project is a great starting point for learning more about QIS. * There are also many STEM youtube channels that are great for learning about QIS such as [Looking Glass Universe](https://www.youtube.com/@LookingGlassUniverse), [Qiskit.](https://www.youtube.com/@qiskit/videos) and [AM](https://www.youtube.com/@Anastasia-Marchenkova/videos). For learning more about math, [3Blue1Brown.](https://www.youtube.com/@3blue1brown) is one of our favorites. | | | |
| **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. | | | |

Appendix

*Schematic board for Activity 2. Print and laminate for easier use*A diagram of a calculator using cards

Description automatically generated

A card game with a diagram

Description automatically generated with medium confidence

*Example of a draw in Activity 2*