PhysicsQuest [2025]: Classical Teleportation

| **Title:** Classical Teleportation  **Subtitle:** An exploration of quantum teleportation with coins  Developed by - Seth Cottrell, Ph.D - City College of New York | | |
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| **Total Time:** 45 minutes  **Audience:** Middle and High School Science Teachers  **Education Level:** Grades 7 - 12 | | |
| **Content Area:**  **Educational topic:** Quantum communication  **Objectives:** Convey the essential idea behind the quantum teleportation protocol, its applications, and why it’s needed.  **Key Question:** Unlike regular information, quantum information is destroyed whenever it is observed or copied. So how can it be sent across networks without being corrupted? | | |
| [**QIS Key Concepts**](https://q12education.org/wp-content/uploads/2023/12/MS-QIS-Key-Concepts-FINAL-12-7-2023.pdf)**:**  **MS Science 5.1 Entanglement**   * When multiple quantum systems in superposition are entangled, their measurement outcomes are correlated. Entanglement can cause correlations that are different from what is possible in a classical system. * When two systems are entangled with each other; the properties of the second qubit cannot be described without considering the first qubit.   **MS Science 8.1 Quantum Communication -** Quantum communication uses entanglement or a transmission channel, such as optical fiber, to transfer quantum information between different locations.  a. Quantum teleportation is a protocol that uses entanglement to destroy quantum information at one  location and recreate it at a second site, without transferring physical qubits | | |
| **Materials** | * 18 coins * Six differently colored pairs of sleeves (e.g., folded 3x5 cards glued or stapled shut) * Binder clips | |
| **Overview:**  Observing quantum information destroys it, making it extremely delicate and difficult to transport from place to place. Quantum teleportation uses a previously established entangled pair (like we saw in the last activity) to “teleport” a piece of quantum information from one location to another without the need to physically transport it over the intervening distance. | | |
| **Teacher Background:**  A “superposition” is a quantum mechanical phenomenon where a single thing exists in multiple states at the same time. The most famous example is the Double Slit Experiment; coherent light (usually lasers) is shined on a pair of slits and then continues on to a screen where we see a series of bright and dark regions called “fringes”. If the light only went through one slit or the other, we’d only see two dots. Because we see many dots (corresponding exactly to wave interference between the two slits), we find we must take the slits into account *together* as opposed to each *individually*.  Remarkably, even when the intensity of the light is turned down so low that only a single photon is allowed through at a time, we find that the photon only hits the screen where there was a bright fringe and never where it was dark. In other words, even when there’s only a single photon, we must always take *both* slits into account. The photon doesn’t go through one slit, and it doesn’t exactly go through both; it takes a *superposition* of paths.  However, if there’s *any* way to know which slit the photon went through, then the interference fringes vanish. This makes superpositions extremely delicate; any interaction that could possibly reveal which state a system is in will destroy the superposition. Qubits cannot survive being “observed” by anything.  In long-distance classical (normal) telecommunication, information (bits) is sent from one repeater to the next. A repeater is a device that listens to an incoming signal, and then repeats it “louder” to send it on to the next repeater in the chain. But because a repeated “looks” at the state of the signal coming to them before repeating it, quantum information (qubits) can’t survive a regular repeater.  Unfortunately, the farther a photon is sent, the more likely it is that any qubit it carries will be destroyed by interactions with the environment. Once light has been sent on the order of ~100km through air or fiber optic cable, quantum information is washed away completely (other methods of qubit storage, like electron spin, fare *far* worse).  So quantum networks need a new kind of repeater that never “looks” at the qubits it’s forwarding down the chain. This is where quantum teleportation comes in. Once point A and point B share an entangled pair, they can be used to send a qubit from one to the other without any qubits making the physical journey.  Actual quantum teleportation requires a lot of sophisticated (expensive) equipment, so rather than using entangled states and qubits (quantum), we’ll use correlated states and bits (classical). Although coins and envelopes are decidedly classical, the procedure is essentially the same. “Classical teleportation” is a (slightly) simpler form of the quantum teleportation protocol. | | |
| **Key Terms (used or presented after the activities - see Foreword for details)**  **Teleportation -** a way to transfer information about a tiny particle, like an atom or a bit of light, from one place to another without moving the particle itself. Instead, it uses a special connection called "quantum entanglement," where two particles are linked even if they’re far apart. When you change something about one particle, the other one reacts instantly.  It’s not like teleporting in sci-fi movies because you’re not moving objects or people—just information about the particle’s state. Scientists think it could help build super-fast computers or super-secure communication systems someday.  **Correlation -** when two tiny particles, like atoms or bits of light, are connected in a special way, so they seem to "know" what the other one is doing, even if they’re far apart. This happens because of something called quantum entanglement.  For example, if you measure one particle and find out something about it, like its spin or direction, the other particle will instantly match up with that, no matter how far apart they are. It’s like a spooky kind of teamwork that scientists are still trying to fully understand. **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**  There are four main activities.  1) generating correlation  2) classical teleportation  The first two are self-contained enough that if you run out of time (or only budgeted a little time), then you can stop there.  3) correlation swapping  4) network teleportation  The third and fourth activities are about how an actual quantum network is run.  Two of the procedures, the “same/different measurement” and the “correlation generation”, look very similar and are easy to confuse so be sure to make the distinction clear. I have found that when I create a correlated pair and then immediately use it to teleport a coin, students tend to lose track of what we’re doing (“why are we clipping and flipping these coins again?”). To avoid that, *first* generate many correlated pairs, and *then* use them to teleport.  **Generating Correlation:**  In the activity the students will create correlated pairs of coins, guess whether they’ll be heads or tails, then reveal one, and guess again. The point this is trying to get across is that “correlated” means “random, but the same”. For example, if all of the coins are always heads, then they aren’t correlated. Correlation implies that learning about one tells you something about the other, but if you know they’re always heads, then there’s nothing to learn.  **Classical Teleportation:**  For younger students you can say “the Far Coin ends up with whichever face the Data Coin had”, but older students may be interested in something a bit more profound: classical teleportation transmits the *probability distribution*. The same/difference measurement is always random and yields exactly one bit of information, so it seems reasonable that you can determine the state of a coin (after all, a bit is any binary choice: 0/1, same/different, heads/tails, etc.). But a probability distribution is substantially more complex than one bit; it could be 50/50, or 30/70, or any other “x/1-x” probability. This ties in to quantum teleportation; a qubit takes a fair amount of information to describe (two complex numbers) and yet quantum teleportation can be done with an entangled pair and two bits (essentially, one for “same/different” and one for “plus/minus phase”).  **Correlation Swapping:**  This is analogous to “entanglement swapping” which should be called “entanglement teleportation”. Since teleportation also sends probability distributions, it also sends correlations. This is the “repeater step” that allows teleportation to be extended to greater and greater ranges (without any particular coin being transported too far).  **Network Teleportation:**  Unlike regular repeaters (which listen for a signal, then repeat and amplify it) correlation swapping can be done in any order. Students may notice that when teleporting across a network they’re doing a chain of correlation swaps (which is the same as a chain of teleportation).  The only relevant piece of information that the students will need to keep track of is the total number of “different” results they get; an odd number of results means “turn the Far Coin over” and an even number means “leave it alone”, since turning the coin over twice is the same as leaving it alone.  During this activity you may need more than the six recommended sleeve pairs if you want to create a non-trivial network (with a couple intermediate hubs and multiple endpoints). | | |
| **Objectives:** To learn the teleportation protocol, why it’s useful (it doesn’t expose information and therefore doesn’t damage quantum states), and to explore it in a few scenarios.  – \*  \*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=3i64xJiqoMY&list=PLgxD9DiwxLGp_3vj3biSPG88gIyU6Vzpz&index=8) 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. “Probability” and “correlation” are the main ideas that the teacher should convey before starting. In particular, students should know that the probability of a coin being heads (tails) is 0.5 and what that means. They should understand that a pair of perfectly correlated coins are still random, but also the same as each other. 4. Quantum superposition and entanglement are fairly advanced topics. If you’re already teaching a course on fundamental quantum theory (AP Physics/AP Chemistry/other high level courses), then feel free to delve into how they’re being applied here. **If not, then the only absolutely essential idea is that quantum states can’t be observed without being ruined.** |
| **Setting Up** | | 1. You’ll need six pairs of colored sleeves for holding coins. For the sleeves use the 3x5 cards. Fold them in half and tape or staple them so that you can’t tell which side is which (that’s important later). **If you staple, make sure to alternate staple direction to there is no front or back. This step will take some time.** 2. You’ll need 18 coins per group. They don’t need to match, but it might be less distracting if they do. |
| **During the Experiment** | | **-Collecting Data**  There is very little data to collect. This experience is about understanding and playing around with a protocol used for quantum communication. When it works, the result is always the same: the state of the coin gets where it’s going. All data collection is done with this aim in mind. See student guide below to understand the activity. |
| **Student’s Guide** | | |
| **Intro:** Quantum superpositions are combinations of distinct states; simultaneously up/down, here/there, etc. Unfortunately, this coherence is extremely delicate. Any interaction that provides information about the superposition destroys the coherence and any advantage of the quantum technology you’re using.  Many applications, like quantum cryptography or distributed quantum computation, require quantum information to be sent from place to place. Normally, to get information from place to place, it’s encoded in something that physically makes the journey, like a written letter or a radio wave. However, interactions with the environment rapidly degrade or destroy quantum information. The solution is not to transmit the quantum information, but to teleport it instead.  Today you will learn to use “classical teleportation” which allows you to send the state of a coin somewhere else without ever finding out what that state is and without ever transporting the coin itself. | | |
| **Objective:** To learn the teleportation procedure and use it to send hidden information from place to place.  After reading the introduction, what is your essential question or objective for this activity? | | |
| **Before the Experiment** | | 1. Obtain (or make) several pairs of colored envelopes/sleeves to keep coins in. Your teacher will fill you in on technique for making sleeves with tape or staples 2. Obtain 18 coins. |
| **Setting Up** | | 1. Make your sleeves according to teacher instructions. 2. You’ll need 18 coins. It isn’t important for them to all be the same kind. |
| **During the Experiment** | | Classical teleportation uses a pair of correlated coins, a “Near Coin” and a “Far Coin”, to send the state of a “Data Coin” from one place to another without physically transporting it.  **Generating Correlation:**  Step 1) Take two coins and make sure they have the same side up (both heads or both tails) and place them into two sleeves that are the same color.  Step 2) Clip the sleeves together and toss them in the air so that you don’t know which sleeve is which.  Step 3) Separate the sleeves, being very careful to never turn either of them over. One of these is the Near Coin and the other is the Far Coin. Until we start teleporting in the next activity, it doesn’t matter which is which.  At this point, both coins will have an equal chance of being heads or tails, but whatever one coin is, the other will be the same. The coins are “positively correlated” (if they were always opposites, then they would be negatively correlated).    *Figure 1: To generate correlation you need to: 1) Place a pair of coins in two sleeves with the same side facing up. 2) Clip them together and toss them in the air. 3) The coins in the two sleeves are now correlated. One is the “Near Coin” and the other is the “Far Coin”.*  **Activity:**  1) Generate six pairs of correlated coins by following Steps 1-3 above.  2) For each Near/Far pair, predict whether they will be heads or tails.  Example table:   | Pair number | Prediction for pair (heads/tails) | Observed State for Near coin | Prediction for Far Coin | | --- | --- | --- | --- | |  |  |  |  |   3) Now look at the Near Coin and make a new prediction about what the Far Coin will be. Record in table. Observe the Far Coin and check your predictions.  **Teleportation:**  It takes three people to teleport a coin: a Sender, a Verifier, and a Receiver. By the end of this procedure the state of the Data Coin has moved onto the Far Coin. Notice that every time you do a teleportation, you “burn up” correlation. If the Far Coin is truly far away, the Verifier may need to call the Receiver on the phone.    *Figure 2: If the Data and Near Coins are the same, then leave the Far Coin alone. If they're different, turn the Far Coin over. Whatever state the Data Coin is in, the Far Coin will be the same. This works whether or not you know what any of the coins are.*    *Figure 3: To teleport you need to: 1) Place the Data Coin in the sleeve with the Near Coin. 2) Clip it and toss it in the air. 3) Check if they are the same or different, and either leave the Far Coin as it is or turn it over depending on the result. 4) The Far Coin is now in the same state the Data Coin was in.*  **Activity:**  Step 1) Generate six pairs of correlated coins, keep the Near Coin nearby and send the Far Coin far away. Be very careful not to turn the sleeve! The Sender and Verifier stay close to the Near Coin while the Receiver stays close to the Far Coin.  Step 2) The Sender prepares six Data Coins in any way they choose: flipping the coin, selecting heads or tails, using a random number generator with weighted probabilities, etc. They record the state of each coin in the data table.  Steps 3-7 are repeated for each trio of coins to teleport the Data Coin’s state to the Far Coin.  Step 3) The Sender places a Data Coin into the sleeve with the Near Coin without showing it to anyone else.  Step 4) The Verifier clips the sleeve (so that the coins don’t fall out) and throws it in the air so that no one knows which side is up.  Step 5) The Verifier takes the coins out of the sleeve, checks to see if they are “same” or “different”, and records the result in the table. It does not matter which coin is which, so don’t try to keep track.  Step 6) The Verifier tells the Receiver the result: “same” or “different”.  Step 7) If the Receiver hears “different”, they turn the sleeve containing the Far Coin over. If they hear “same”, then they leave the sleeve alone.  Step 8) The Receiver reveals each of the Far Coins and records the result on the data table.  **Correlation Swapping:**  Not only is the state of a coin teleported, but its relationships and correlations to other coins are teleported as well. Start with two pairs of correlated coins: “Near/Far pair A” and “Near/Far pair B”. If you use “Far A” as your Data Coin and use pair B to teleport it, then Near A and Far B will now be a correlated pair.    *Figure 4: To swap correlation you need to: 1) Start with two pairs of correlated Near/Far Coins, with Far A and Near B close together. 2) Place Far A into the sleeve with Near B without looking at it. 3) Clip it and toss it in the air. 4) Check if they are the same or different, and either leave Far B as it is or turn it over depending on the result. 5) The remaining coins, Near A and Far B, are now correlated.*  **Activity:**  1) Generate six pairs of correlated Near/Far Coins. Three of these are the “A pair”, three are the “B pair”.  2) Use “Far Coin A” as a Data Coin and teleport it in the same way. The only difference here is that you need to be careful to never find out what the state of the coin is, so instead of preparing the Data Coin and putting it in the Near Coin sleeve, just “pour” Far A from its sleeve to the sleeve for Near B without looking at it.  3) Verify that Near A and Far B are now correlated by revealing each pair.  **Network Teleportation:**  It would be impossible to directly connect every computer with every other computer in the world. Instead, everything connects to network hubs which connect with each other. The same thing can be done to make it possible to choose where you want to teleport your coin. The network hubs are collections of differently colored sleeves. If two hubs share a Near/Far pair, then they are connected and can teleport or swap correlation between them.    *Figure 5: A network of correlated pairs. Two “nodes” are connected if they share a Near/Far pair. Using correlation swapping and teleportation, a Data Coin can be teleported from any node in the network to any other.*  **Activity:**  1) Generate six pairs of correlated Near/Far Coins.  2) Create a network of correlated pairs (see figure 5).  3) Randomly choose which endpoints you want to use to send and receive a Data Coin.  4) Use correlation swapping to correlate the two end points (turning them into a new Near/Far pair).  5) Teleport the Data Coin. |
| **Conclusion** | | 1. What did you learn about the concepts of superposition, entanglement, and teleportation based on this activity?  2. What could you see this principle being used for in the real world?   1. What myths or misconceptions about teleportation has this activity changed for you? |
| **Additional Resources:**   * This experiment was originally introduced in “Quantum Computation: An Introduction for Undergraduates”, which is available for free here: <https://www.dropbox.com/scl/fi/xhtoatg130cgs4upo5lrk/Cottrell.pdf?rlkey=jvdm98ihov83pjxugwpcrsd3n&dl=0> | | |
| **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. | | |