The Physics Teacher

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Cite as: Phys. Teach. **59**, 613 (2021); https://doi.org/10.1119/5.0019871
Published Online: 27 October 2021

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Entanglement Ball: Using Dodgeball to Introduce Quantum Entanglement

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Quantum computers are at the forefront of computing; however, few people understand how they work and their capabilities. We present two versions of an interactive activity designed for high school students (ages 13 to 18) that introduce a core quantum concept—*entanglement*. The first version illustrates a simple connection between two particles, and the second explores different ways that two particles could be entangled. This activity works well for entry-level quantum computing learning and requires minimal materials.

What is quantum entanglement?

In classical computers, information is stored in binary digits, or *bits*, which exist in a state of 0 or 1 (also referred to as "on" or "off"). Classical computers are anything from a smartphone, to a laptop, to a supercomputer. Quantum computers, on the other hand, are unique because they harness quantum physics by storing information in entities that can be in two states at the same time—0 and 1—referred to as *superposition*. This might occur in the spin (up or down) of a single atom or in the polarization (horizontal or vertical) of a photon. These entities, when used to store information in a quantum computer, are referred to as quantum bits or *qubits*. While qubits can exist in superposition, measuring or observing the qubit will force it to collapse into one of the two states, which are labeled 0 or 1. *Entanglement* is when two or more qubits are linked together, meaning their outcomes of being 0 or 1 when measured correspond to each other in some way. Though it is not a perfect example, you can think of a pair of entangled qubits like a pair of gloves. If you and your friend each have one glove in the pair, but you do not know who has the left one and who has the right one, you need only look at one to know the other. In other words, if you have the left-handed glove, your friend must have the right-handed glove. Thus, just by knowing information about one part of the pair, you automatically know information about the other part of the pair. This is true for entangled qubits. However, the ways in which they relate to one another may vary. This ability to be manipulated into different relationships is what is useful to quantum computer scientists.

While in superposition, a qubit is guaranteed to collapse into a single state if measured, either into 0 or into 1; however, the probability of collapsing into 0 over 1 or vice versa is infinite. *Gates* in quantum computers are mathematical operations that manipulate the probabilities of these outcomes. For example, a Hadamard gate forces a qubit to have a 50% probability of collapsing to a 0 and a 50% probability of collapsing to a 1, similar to the odds of flipping a coin heads or tails. If we have two qubits, operated on by a Hadamard gate, the probability of measuring two 1's would be 25%, two 0's would be 25%, and a 1 and a 0 would be 50% (Fig. 1). However, when multiple qubits are entangled, their measurement outcomes are correlated. Two qubits could be entangled such that their outcomes will match—if the first qubit is a 1, the second one must also be a 1, and, likewise, if the first is a 0, the second must also be a 0. This would force the probability of getting two 1's to be 50% and the probability of two 0's to be 50%, with no probability of getting a combination of a 0 and a 1 (Fig. 2). This forced probability happens when the first qubit is measured and collapses into either 0 or 1, which causes the second qubit to collapse into the same state. Two qubits can be entangled in several ways, including to be in opposite states, so that entanglement results in the second qubit collapsing into the opposite state of the first. The nature of entanglement depends on the quantum gate used to establish entanglement as well as subsequent operations on one or both of the qubits.

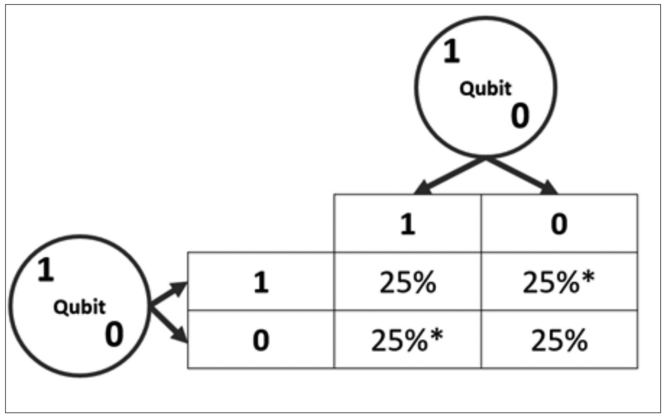

Fig. 1. Probability of different outcomes for two qubits that are not entangled. *_Note_: These percentages add up to the 50% total for the combinations of one "1" and one "0".

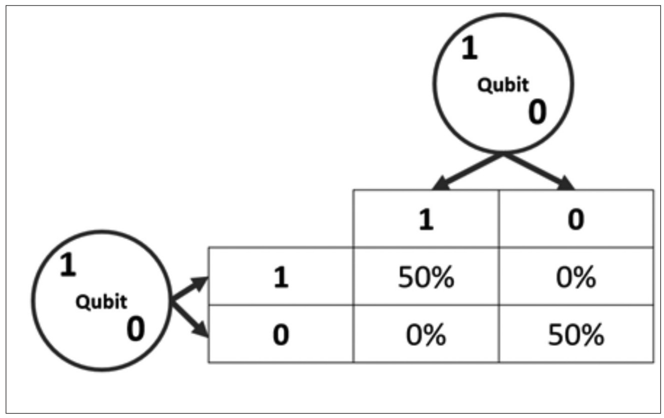

Fig. 2. Probability of different outcomes for two qubits that are entangled to be in the same state.

Entanglement is part of what gives quantum computers greater power than classical ones. With more complex ways to store data through entanglement, quantum computers have the potential to solve more complex problems on a much faster timescale. Additionally, unlike classical computers with bits, quantum computers with qubits increase their power exponentially with every qubit that is added to the system. However, although entanglement is useful for accessing the potential power quantum computers possess, it comes with trade-offs. More than two qubits can be entangled to create increasingly complex ways to store information, but increasing entanglement decreases the stability of the quantum computer. Note that the activity described here presents a simplified idea of entanglement and considers only pairs of qubits.

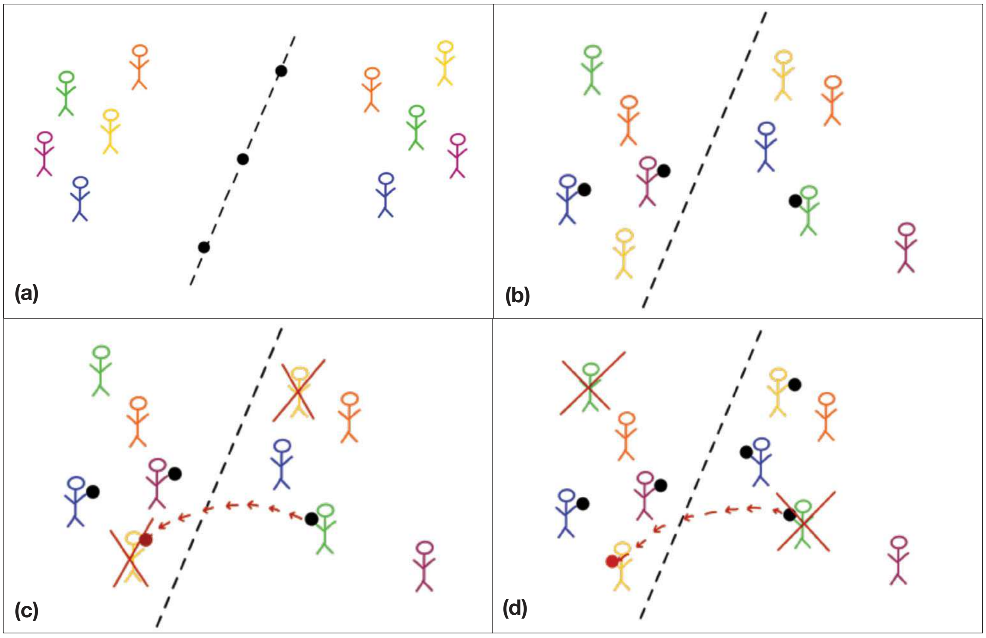

Fig. 3. Representation of round 1 game play. Partnerships are indicated by similar colors. The black dotted line separates the court into two sections. The red ball indicates the final position of a thrown ball and the red X's indicate student elimination. (a) Starting position. (b) Begin game play. (c) Elimination of the yellow pair by a yellow player being hit with a ball. (d) Elimination of the green pair by a yellow player catching a ball thrown by a green player.

Understanding entanglement and how qubits get measured is important because if a qubit is altered, the information that it holds is altered. Think about getting an error on your calculator due to incorrect syntax, but now, with qubits, you may get an error when photons from external light interfere with the system. On the level of classical physics, which we are familiar with in our day-to-day lives, light particles pose no threat to our computing systems. However, on the quantum level, something as simple as the energy from light particles can destroy a quantum computing system. The more qubits and entangled relationships a quantum computer scientist has to care for, the greater the possibility of experiencing an interruption to the system and being unable to complete their work. Thus, understanding entanglement lets us better understand the great complexity and fragility of a quantum computing system.

For a more in-depth explanation of quantum entanglement and other quantum concepts, see further educational resources, including articles, zines, and videos.[1-4]

Research context

The activity was part of a course titled "Quantum Race: An Exploration into Quantum Computing" offered as a weekend program for high school students taught by university graduate students. Enrolled students explored 10 quantum computing topics, ranging from machinery to superposition, using short lectures and interactive activities over the course of five two-hour Saturday classes. In the development of this activity, students were first introduced to the concept of entanglement through a 10-minute virtual lecture from a Princeton University graduate student who studies quantum entanglement. Following this lecture, we led the students in the entanglement activity designed for college students, written by López-Incera and Dür, that was intended to connect the theoretical concepts to embodied representations.[5] After the lecture and activity, a few students said they learned things about entanglement, such as "that entanglement is a non-classical property of the world," and "you can have the state of one particle from the state of another." However, we found that this activity was ultimately too complex for high school students, with exit survey responses stating, "I kinda didn't understand the game," "I think the dodgeball thing was good. The representation of data was a little convoluted at the end and I was very confused on the point you were trying to make," and "I would like further clarification on entanglement because I kind of lost it there." Recognizing the need for a simplified representation of entanglement to use at the high school level, we adjusted López-Incera and Dür's activity to introduce entanglement to high school students. We refer to the adapted activity as Entanglement Ball.

Using dodgeball to illustrate entanglement

This activity requires at least six students evenly divided into two teams, soft dodgeballs (at least three, or two fewer than the number of students per team), and an open, flat space.

Traditionally, dodgeball involves two teams, with a line dividing the play space into two equally sized sections. Before play begins, students line up parallel to the center line dividing the court as far away from each other as possible. The dodgeballs are placed on the center line. When play begins, all players run towards the center and attempt to grab a ball (since there are more players than balls, only some players will successfully get a ball initially). During play, players must stay on their own side of the court and attempt to hit players on the opposite side with a ball. If a player is hit with a ball and does not catch it, the hit player must exit the court and sit on the sidelines for the remainder of the game. However, if a player catches a ball that is thrown at her, the player who threw the ball must sit on the sidelines. The goal is to eliminate all players on the opposing team, ending the game. The team with at least one remaining player wins. The two versions of Entanglement Ball involve an identical setup. Either of the two iterations of the activity can be implemented to introduce entanglement to students; however, completing both activities sequentially will result in a more extensive introduction to entanglement.

Entanglement Ball – Version 1: Simple entanglement

Simple Entanglement Ball introduces the idea that actions done on one qubit affect the qubit(s) it is entangled with. Players in this version act as qubits and are entangled with a player on the *opposing team*. Entangled pairs are established before game play with the partners separating over the center-court line just as at the beginning of a classical dodgeball game [Figs. 3(a) and (b)]. It should be explained to the students that, in the game, entangled pairs are always in the same state as one another. That is, they are either both "in play" or both "out of the game" —the actions on one half of the pair affects the state of the other player. (Recall that this is only one possible way that actual qubits could be entangled. Entanglement could result in other outcomes such as opposite states.) In classical dodgeball, when a ball hits another player, that player is eliminated from the game. In Entanglement Ball, both the player who is hit and the player's entangled partner (who is located on the opposing team) are eliminated [Fig. 3(c)]. The same is true in the event that a player catches a thrown ball. The thrower and their entangled partner are simultaneously eliminated [Fig. 3(d)].

Rather than trying to eliminate all players on the opposite team, each entangled pair acts as their own team, trying to eliminate all other entangled pairs. The last entangled pair standing wins. This is a simple illustration of the word entangled in that the state of one "entangled" player affects their partner's state. However, this does not represent *how* qubits are acted upon, or measured, since qubits would be measured by an external source, not by another qubit.

Entanglement Ball – Version 2: Multiple types of entanglement

Version 2 demonstrates that entanglement involves a connection between qubits and that there are multiple ways of entangling qubits.

Like in Entanglement Ball - Version 1, students in Version 2 represent qubits. However, unlike the first version, the states are not "in" and "out," but rather "sitting" (which we call 0) or "standing" (which we will call 1). Also they can be entangled in the same *or opposite* state as their entangled counterpart, depending on the round.

Round 1. Each player is in the same state as their entangled counterpart. This means that if a player is sitting, his entangled counterpart on the opposite team is also sitting. Both players would be in a 0 state so the pair could be described as being in (0, 0). In contrast, if a player is standing, her entangled counterpart on the opposite team is also standing. In other words, the pairs are either in the state (1, 1) or (0, 0). In this round, it should not be possible for a player to be sitting while her counterpart is standing. So (0, 1) and (1, 0) are impossible combinations.

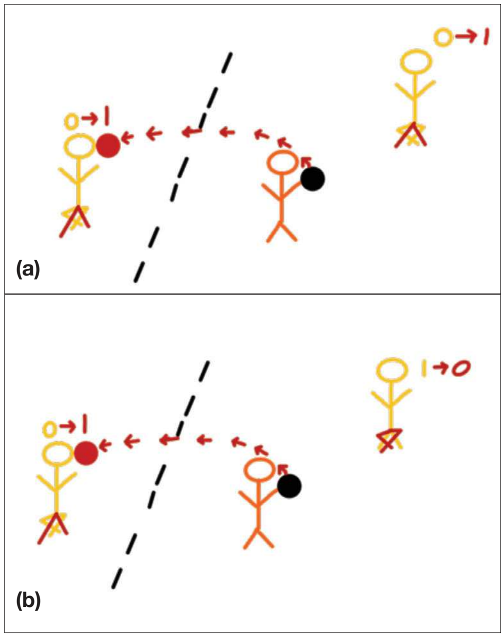

Fig. 4. Representation of Entanglement Ball Version 2. (a) Round 1 with partners similarly entangled. When one player is hit, they both change to the same new state (ex: 0 → 1). (b) Round 2 with partners oppositely entangled. When one player is hit, they both change to the opposite new state (partner A goes from 0 → 1 and partner B goes from 1 → 0).

Before game play, each entangled pair is told their initial states (0, 0) or (1, 1) by the teacher, ensuring an even distribution of the 0 and 1 starting states.

Students assigned to be in the 0 state begin the activity sitting. Being in a sitting position means the students may not move from that position; however, they may throw and catch balls. We recommend foam balls over rubber ones, so the sitting participants are not injured. (If safety is still a concern, consider another way to distinguish 0 from 1.) Players in the 0 state choose where on their side of the court to sit when game play begins. Students assigned to the 1 state begin the activity standing, and they, along with the others in the 1 state, run to the balls when game play begins, as described earlier [Fig. 4(a)].

When students get hit by a ball or throw a ball that is caught, their state (and their entangled partners' state) switches from 0 to 1 or 1 to 0. That is, they go into the opposite state as the one they were in [Fig. 4(b)]. If they were standing, they now go to a sitting position and vice versa. Because no students are eliminated in this version, thus no winner is established, both rounds must have a determined endpoint, such as a time limit (we recommend 5 to 10 minutes of game play).

Round 2. Round 2 follows the same rules as round 1, except that all pairs are oppositely entangled. That is, each pair has a student assigned 0 and a student assigned 1 (one sitting, one standing). The game continues as described in the instructions for the first round of Version 2.

Students should come away with the understanding that qubits can 1) be entangled and 2) be entangled in different orientations. This iteration demonstrates the basic idea that quantum computer scientists can manipulate qubits by entangling them in specific orientations to store information.

Student response

This high school level entanglement representation was tested out with the students two weeks after the López-Incera and Dür[5] activity. In the time between this activity and Entanglement Ball, students received lectures and participated in activities around the potential of quantum computing, reversibility, and the measurement of qubits. During a full-class discussion after engaging in Entanglement Ball, we found that all of the students expressed a greater comfort and understanding of entanglement. Immediately following the activity, the majority of the class raised their hands when asked if they felt this activity was a better experience than the original dodgeball activity from two weeks prior. In class discussion, students described entanglement as being affected by whatever happened to their partner. In an exit survey, one student expressed they felt they had "learned about how quantum entanglement works," and another said they learned "how quantum entanglement is done." While we did not evaluate their knowledge of entanglement in any formal or in-depth way due largely to time constraints, the consensus was this activity produced a better sense of having learned something and greater clarity about entanglement overall. In addition, students were able to make more connections to other areas of quantum computing they previously had not. For example, having previously learned about measurement, students identified that "getting hit" by a dodgeball was representative of measuring a qubit, which would lead the qubit to collapse into being 1 or 0. They also recognized that qubits were always in a 0 or 1 state once measured. In other words, they could be sitting or standing after getting hit by a dodgeball but not both. One student remarked that they "liked how we played dodgeball to help us learn," and four of 11 course survey responses indicated that entanglement was the most interesting topic they had learned. After Entanglement Ball, there was only one more session remaining in the course, and no further activities were conducted with an explicit focus on entanglement.

While the use of Entanglement Ball in this course was as a pilot-type trial, we would hope to better integrate the learning goals of this activity into a greater context. We feel it was a worthwhile activity, as the students genuinely enjoyed it and seemed to have more comfort with the terms and ideas that were conveyed through it. However, we believe it has the potential to engage students in discussion more deeply than was experienced here if used as part of a larger unit on quantum mechanics and/or quantum computing, primarily as a way for students to make connections between their hands-on experience in the world of classical physics to the nature of qubits in the world of quantum physics. Class discussions integrating this activity into larger units on quantum computing could center around the practical application of entanglement in building quantum computers or the mathematical implications of entanglement with superposition to support exponential computing power increases. Alternatively, this activity could serve as an informal assessment of student understanding through discussions about what each aspect of the game represents in the quantum computing world and the strengths and weaknesses of this simple representation.

Discussion

As quantum computing becomes more relevant to the general population, an increasing need exists for students to be familiar with the concepts, vocabulary, and impacts of quantum computing. At present, courses in quantum computing are available primarily in higher education. There do exist several great resources for visualizing quantum phenomena; however, these are all visual computer simulations that may be difficult to understand for younger students.[3, 4, 6] Finding avenues to present quantum computing in an interactive and engaging way is important for reaching a younger audience. Teacher preparation for this activity includes discussing qubits and superposition with students prior to game play, but it is worthwhile for meaningful engagement. Teachers may also have follow-up discussions on, for example, relating Version 2 to the way quantum computer scientists specify how entangled relationships of qubits operate in order to be intentional about information storage. This activity is not a perfect analogy for entanglement, and further work is needed to inform development of activities that incorporate all aspects of entanglement and superposition accurately, but we believe it is useful for introducing the core ideas of entanglement in an engaging way for students. Further research in this area could explore what conceptual models of entanglement look like for students before and after engaging in this activity, and/or how prefacing the activity with discussions about qubits and superposition (or possibly other quantum computing concepts) affects students' learning outcomes from the activity.

Acknowledgment

This material is based upon work supported by EPiQC, a National Science Foundation Expedition in Computing, funded under grants 1730088 and No. 1730449. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

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