Teaching quantum entanglement with card games

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Simple interactive activities help non-expert audiences to grasp the core concepts of quantum entanglement and the Nobel Prize-winning experiments that proved how quantum mechanics defies classical physics.

Even compared with other fields of cutting-edge research, the underlying principles of quantum mechanics are often deeply complex, and can contradict our everyday intuitions about reality. When communicating these ideas beyond the scientific community, this makes it incredibly challenging for researchers to simplify concepts enough to make them approachable, without sacrificing accuracy.

Through new research published in EPJ Quantum Technology, Valentina De Renzi at the University of Modena and Reggio Emilia, Matteo Paris at the University of Milan, and Maria Bondani at Italy's Institute for Photonics and Nanotechnologies present a new approach for introducing the concepts of quantum entanglement, and its experimental proof through the violation of Bell's Inequality – whose experimental demonstration earned the 2022 Nobel Prize in Physics.

Based on encouraging feedback from participants, the team are hopeful that their approach could be easily integrated into school curricula, and could also be applied with other non-expert audiences: including policymakers, industrial stakeholders, and the general public.

As part of the Italian Quantum Weeks project in 2024, De Renzi, Paris, and Bondani presented their approach through an exhibition named Dire l'indicibile, meaning "Speaking the unspeakable". Its interactive activities included a card game and a simplified staging experiment, which allowed participants to explore fundamental differences between the classical and quantum worlds.

The card game involves ordinary playing cards with coloured backs (blue or red) and ordinary fronts (black or red suits). Firstly, a dealer creates two decks in a specially prepared order, and gives one to each player. In this way, each card is paired with that in the same position in the other player's deck. Each player then measures both colours on every card, assigning numerical values (+1 for red, -1 for blue or black) – making sure to keep their deck in its original order.

By combining these values according to a specific formula, each pair produces a score of either +2 or -2. When averaged across all pairs, the final result must fall between -2 and +2 – a mathematical limit that applies to all classical systems where both properties can be measured simultaneously.

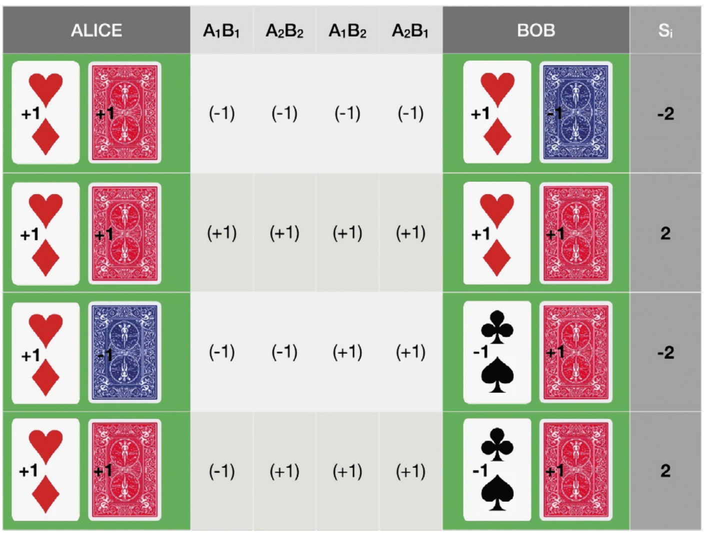
In contrast, the staging experiment recreates the key steps used to detect quantum violations of this limit. Again, a dealer prepares paired cards, but this time each card is sealed in a box, allowing only one colour to be measured. Players flip coins to randomly decide which property to observe, mimicking the constraint in quantum experiments where measuring one property makes the other undefined. After collecting these partial measurements, the dealer calculates the average correlation in the same way as before.

In this classical staging, the result still obeys the -2 to +2 limit – but in genuine quantum entanglement experiments, this bound can be violated, reaching values up to approximately + or -2.83. This violation proves that quantum correlations cannot be explained by any classical theory, no matter how cleverly constructed – revealing something fundamentally different about how nature operates at the quantum level.

By demonstrating both the experimental procedure and why classical systems are bounded, De Renzi's approach effectively communicates just how profoundly the quantum world differs from our everyday experience. The team hopes this method could lead to new breakthroughs in making quantum mechanics accessible to a diverse range of audiences. ■

Reference

[1] V. De Renzi, M.G.A. Paris & M. Bondani, *EPJ Quantum Technol.* **12**, 122 (2025). https://doi.org/10.1140/epjqt/s40507-025-00415-5



$$< S > = \frac{\Sigma_i S_i}{N} = 0$$

$$< S > = < A_1 \cdot B_1 > + < A_2 \cdot B_2 > + < A_1 \cdot B_2 > - < A_2 \cdot B_1 >$$

◂ Understanding violation to Bell's Inequality with a card game.