Entangle me! A game to demonstrate the principles of quantum mechanics

Andrea LÓPEZ-INCERA and Wolfgang DÜR

Institut für Theoretische Physik und Institut für Fachdidaktik, Bereich DINGIM, Universität Innsbruck, Technikerstrasse 21a, A-6020 Innsbruck, Austria.

Abstract. We present a game to illustrate the principles of quantum mechanics, where students play the role of quantum particles and scientists. By playing and experiencing first-hand how it is to be a scientist working with quantum particles, the students can learn not only basic concepts of quantum mechanics such as the superposition principle or the Heisenberg's uncertainty relation, but also advanced concepts such as entanglement, decoherence or quantum cryptography.

1 Motivation

Quantum mechanics is a subject that is notoriously difficult to teach in class. In addition to the conceptual difficulties that are intrinsically connected to its counter-intuitive features, an in-depth understanding requires advanced mathematics.

We suggest a game where students play the role of both scientists and quantum particles and experience how the rules of quantum mechanics work, and what they imply for the properties of systems. This allows them not only to play and behave as scientists, but helps them to internalize the non-classical features and strange properties of a quantum world.

2 Theoretical framework

We make use of the qubit approach to quantum mechanics [1,2]. In contrast to a classical two-level system, a qubit can be in a superposition of two states,

$$|\psi\rangle = \alpha\,|0\rangle + \beta\,|1\rangle \qquad (1)$$

In particular, in addition to the (classical) basis states $|0\rangle\,|1\rangle$ (z basis), superposition states $|\pm\rangle = (|0\rangle \pm |1\rangle)/\sqrt{2}$ (x basis) are possible. If a superposition state like this is measured in the z basis, the outcome is random, and the resulting state is changed to a non-superposed state.

For systems of two qubits, the superposition principle leads to the possibility of entangled states, e.g. of the form $|\phi^+\rangle = (|0\rangle|0\rangle + |1\rangle|1\rangle)/\sqrt{2}$. Entangled states lead to perfectly correlated measurement results for both qubits when they are measured in both the x and the z basis.

3 Entangle me!

The game we propose is divided into several parts, each of which illustrates a given concept of quantum mechanics: part 1 is focused on the superposition principle and qubit states, and part 2 works on entangled states of two qubits (see Sec. 2). In addition, a third part can be included to explain decoherence, that is, a more realistic scenario in which particles are not isolated, but they interact with the surroundings.

Firstly, the students are arranged in groups: one group plays the role of quantum particles and the other one plays the role of scientists. Particles act accordingly to simple rules only they know, and that correspond to the actual behaviour of quantum particles. Scientists should figure out the rules (i.e. physical laws) by observation, i.e. by preparing particles in specific states and by performing measurements. To do so, scientists first have to run and catch the particle!

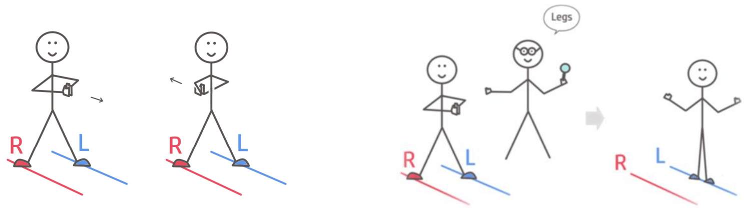

Fig. 1. Left: Superposition state $|+\rangle$ and $|-\rangle$ respectively. Right: Example of measurement of the "leg" property.

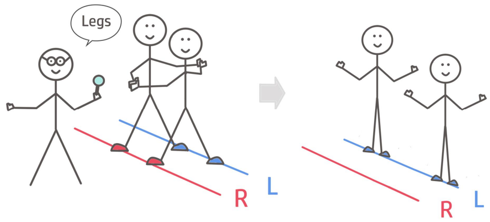

Fig. 2. Measurement ("leg" property) of the state of an entangled pair of particles.

3.1 Part 1. Single particles.

Like a quantum particle, a student can also be in a superposition state because, if there are two lines on the floor, he/she can stand on both lines at once by putting each foot on one line (see Fig. 1). Thus, the states $|\pm\rangle$ are represented as in Fig. 1 Left, whereas for the states $|0\rangle$ ($|1\rangle$) the student stands with both legs on the left (right) line and outstretched arms.

Two different kinds of measurements can be performed by the scientists: "legs" (corresponding to z-measurements, with outcomes left and right), or "arms" (corresponding to x-measurements, with outcomes front and back). As an example, if the scientist measures the "leg" property of a particle that is in a superposition state $|\pm\rangle$, the particle can choose to jump to the left or right line randomly and announces the result (see Fig. 1 Right). If the particle was already with both legs on one line, he/she simply announces the state.

3.2 Part 2. Entanglement.

In this part, particles can get entangled: they face each other, hold hands and stand with their feet on different lines (see Fig. 2). Particles in this state react randomly to a measurement of both leg or arm property. The rule for them now is that, if the first particle is measured, the particle acts according to the rules explained in Sec. 3.1, and the second particle must change its state in the same way as the partner, without even being measured! (see Fig. 2). Scientists will obtain correlated results for both the leg and arm property, when measuring an entangled pair.

4 Conclusion

We have introduced a game with simple rules that allows one to illustrate the basic principles of quantum mechanics, and to directly experience them. In addition, students can act and work like a real scientist, developing theories and testing them.

References

[1] W.Dür, S.Heusler, Visualizing the invisible: The qubit as a key to quantum physics, *Phys.Teach.* **52**(2014) 489.

[2] W.Dür, S.Heusler, The Qubit as key to quantum physics Part II: Physical realizations and applications, *Phys. Teach*. **54** (2016) 156.