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Introduction to Quantum Computing **Project Task #03**
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There is a whole scientific community interested in providing an indisputable proof that nature violates Bell's inequality. Explain why the Big Bell Test assures that they closed all the loopholes and what does it imply for our understanding of the universe.

Bell's theorem put forth a framework of experiments, which would put an end to the Einstein-Bohr debates. In short, Einstein believed in local realism, the idea that physical objects have properties regardless of having been observed, and that nothing travels faster than the speed of light, and his explanation for the "spooky action" he encountered in the quantum world was that there is a hidden variable which, if accounted for, would provide a more complete theory of quantum mechanics. Bohr, on the other hand, believed that some of these properties did not really exist until they were measured. Bell suggested an experiment, in which, if the local hidden variable theory was true, a certain inequality would be satisfied. A violation of this inequality would disprove Einstein's theory that quantum mechanics is incomplete, and would supporting evidence that quantum mechanics is actually complete, and these quantum objects do really behave in a weird way.

Countless experiments, known as **Bell Tests** have been conducted, proving time and time again that quantum mechanics violates the Bell Inequality. As is the case with all experiments, Bell Tests are also subjects to loopholes, and local realists had hopes that failure of addressing these loopholes was the reason that quantum mechanics was found to be inconsistent with local realism, and believed that if these loopholes were addressed, then quantum mechanics would prove to be actually consistent with Einstein's beliefs. One of these loopholes is the **Freedom of Choice** loophole, which challenges the fact that the measurements made by Alice and Bob are made independently, where Alice and Bob are the detectors which perform the measurements of the entangled particles. In other words, that the determinism doesn't come from the particles themselves, but from the measurement choices of Alice and Bob, which are somehow predictable, and hence, deterministic. This loophole would essentially allow for a local realist theory which would be consistent with quantum mechanics.

Unfortunately for local realists, **The Big Bell Test** collaboration came up with a model of experiment that would also close the freedom of choice loophole, largely putting the question of quantum completeness to rest. There are strict conditions which make the outcome of a Bell Test credible. In addressing the freedom of choice loophole, the most important condition is making sure that the measurement choices are independent. The way that The Big Bell Test made sure of this complete unpredictability and independence was that they made use of the consciousness of human beings. They deployed 100,000 people on the day of the test, to input random sequences of 1's and 0's either through a plain interface on their website where users would just input these sequences as fast as they could, or through a video game, where the 1's and 0's represented moves in the game. These sequences were then randomly sent to the experiment labs, where they were used to make the measurement decisions, this way, completely ensuring the independence of the measurement choices, and ultimately, closing the freedom of choice loophole relying on the consciousness and free will of human beings, as well as on the large number of participants, which ensures the statistical significance of the results of the experiment.

Gamification is a powerful tool that can be used in several contexts, such as marketing and generation of products. Explain how The Big Bell Test experiment utilized gamification for generating random numbers and imagine and discuss other possible applications of gamification in quantum computing

An important challenge in most Bell experiments has been collecting a large enough sample of human generated choices for a statistically significant result. The Big Bell Test utilized the idea of gamification to get the desired statistically significant sample, and using simple reward systems to encourage users to play more games, thus, generating more input for the experiment. The game consists of two different types of sub-games, both restricted by time, the first is going through a path, where the player can move forward either by entering a 0 or a 1, and the goal is to be as unpredictable as possible, all the while collecting a required number of atoms throughout the path. The second type of game is also a variation of entering 1's and 0's, this time, after each entry, the prediction of an oracle is revealed, and if the oracle guessed the entry correctly, the player loses, otherwise, the player wins. The objective of the game is to be as unpredictable as possible. In both types of games, machine learning algorithms are used to predict the player's inputs, modelling them as Markov processes, and updating the predictions using reinforcement learning. The game, while using some reward mechanisms to keep players interested, mainly relied on people's willingness to contribute to the experiment's success, and be a part of an important milestone in quantum research. This was the process behind the random number generation used in the experiment.

Gamification can be useful in other areas of quantum computing, more specifically, in teaching quantum computing. For example, explaining Bell's inequality itself, where students can be Alice or Bob, and they would have the choice of measuring in certain basis, getting rewards if both Alice and Bob get the same measurements, and having a target correlation as a score, and other parameters of the inequality can be incorporated into the game, and game modes can include local hidden variables, where the game would allow for some sort of communication between Alice's and Bob's particles, to show which modes violate the inequality, and which modes do not.

Choose two of the thirteen nodes of the Big Bell Test experiment and compare their physical system, degree of freedom measured, rate of bits consumed and total number of bits, how where the bits used, how long the experiment took, and the distance between Alice and Bob.

The nodes I will be comparing are Node 6 and Node 7, the experiments done at LMU in Munich, Germany, and at ETH in Zurich, Switzerland respectively.

Node 6 (LMU) The physical system used to prove the inequality is a spin of a single trapped atom, entangled with the polarization state of a single photon, with a distance of 400m between Alice and Bob. They used two DoF's, spin and polarization. The experiment lasted for 13 hours, where 39614 events were collected. The atomic measurement directions of 19716 were chosen by humans, and the rest were done by a Quantum Random Number Generator, or a QRNG. The peak rate at which bits were used was 1.7 bps. Both sets of measurements showed strong violations of the Bell Inequality, with Bell parameters of 2.427 ± 0.0223 and 2.413 ± 0.0223 respectively, and the differences between the two sets of measurements showed no statistically significant difference.

Node 7 (ETH) In this experiment, two superconducting qubits were used with a distance of 1mm between Alice and Bob, using the charge degree of freedom (as far as I understand). The experiment lasted for 48 hours, 16.34 million human generated random numbers were used to make 8.17 million Bell measurements, 7.96 million of which had successful state initialization and calibration. The peak rate at which bits were used was 3 kbps. The Bell parameter S was 2.271 for the case where the entire dataset was used, and 2.307 for the case where datasets with failed calibration were not used.