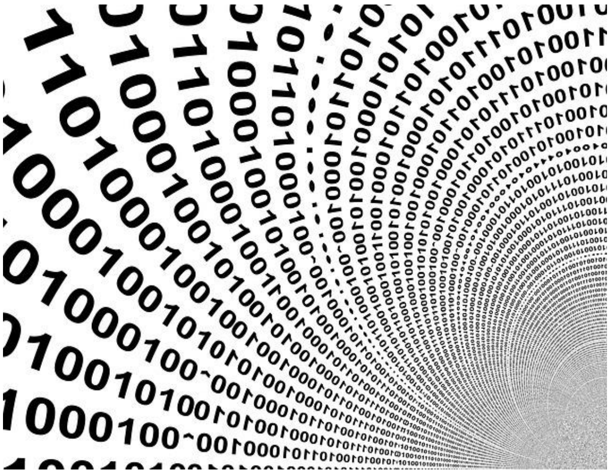
Why isn't Nature more spooky?

Physics usually concerns itself with space, time, particles and forces. But some theoretical physicists suggest that the most fundamental constituent of Nature may actually be information. Some even go so far as to suggest that the universe itself is in fact a computer. But if that's the case, then it cannot be the kind of computer that we currently use in our schools, offices and homes. These are what physicists call classical computers. Rather it must be a quantum computer. What is a quantum computer? Well, simply put, it's a computer that harnesses those phenomena described by quantum mechanics: one of physics' two most important theories (the other being Einstein's general theory of relativity).

Quantum mechanics works amazingly well when it comes to predicting the behaviour of light and matter on the atomic scale. No one has ever managed to refute it experimentally and much of our modern technology is based upon it. It would be impossible to understand how DVD players or even fridge magnets work without quantum mechanics. Yet we are still to unleash its full potential. Right now, scientists the world over are racing to create a full-scale quantum computer. However, unlike relativity theory, quantum mechanics is based on very abstract mathematical principles, and there is no consensus on what they really mean or where they come from. In fact there are at least half a dozen interpretations of the theory. It was a desire to better understand this successful, but non-intuitive, area of physics, that led me to a Master's project on quantum nonlocality.

Nonlocality, which Einstein famously referred to as "spooky action at a distance", is one of the strangest properties of quantum systems, but also one of the most useful for computation. To get a feel for it, imagine two programmers with extremely powerful classical (not quantum) computers that are connected via a network cable. A two-part system (for example a pair of atoms) is called nonlocal if it yields measurement outcomes which our programmers can never hope to simulate on their computers unless the signal between them were able to travel infinitely fast (contradicting relativity). The standard way of describing this in quantum mechanics is to say that the outcome of an experiment at one point in space can instantaneously affect the outcome of another experiment at some other point, no matter how far away. This is a truly remarkable fact about the universe we live in, but no one can really claim to know how it works.



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If the universe is ultimately made up of information, then it cannot consist of classical bits (pictured here). Nonlocality implies that it must consist of quantum (or possibly superquantum) bits.

What we do know though, is that quantum nonlocality does not allow information to be transmitted from one place to another. The reason is that, although experimental results may be correlated over large distances, these results are always random. It is this inherent quantum randomness which stops us from using nonlocality to send messages faster than light—something relativity says is impossible.

In my project, I have been classifying the nonlocality of various two-part systems and trying to understand what makes quantum mechanical "spookiness" unique. The driver behind this work is the fact that quantum mechanics predicts only a certain level of nonlocality. So the big question is: why is Nature not *even more* nonlocal, i.e. superquantum? In principle, Nature could be perfectly nonlocal and still not allow faster-than-light signalling. But such superquantum nonlocality has never been observed, and various arguments inspired by computer science have been proposed over the last few years which might explain why we can rule it out.

Understanding the nonlocality of general multi-part systems is a huge outstanding problem in the field of quantum information. Such an achievement would give us deeper insights into quantum mechanics and maybe even clues towards solving physics' greatest mystery of all: how to unify quantum mechanics and Einstein's general theory of relativity. At the same time it will likely have very practical applications for quantum information processing, allowing our grandchildren to get the most out of their quantum computers.

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