The History of Entanglement
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Entanglement is one of the biggest mysteries facing physics today. Depending on who you ask, they will either tell you entanglement is not understood but the equations just seem to work out (shut up and calculate), or they will tell you that entanglement is meaningless and can be disregarded. Neither of these answers are satisfactory, because if we are going to reconcile the geometric theory of General relativity with the particular theory of Quantum fields, we must have a better understanding of entanglement. The purpose of this paper is aimed to provide the readers with the perspectives of entanglement throughout history. As with most concepts in physics, a suitable analogy serves to provide a deeper understanding of physical phenomena.

Between two great cliffs hangs a rope bridge with wooden planks and it is not certain whether the trees on which the ropes are fastened to will snap or not. Upon approaching the bridge, the physicist immediately questions the integrity of the whole bridge; is the force of my mass greater than the strength of the rope? Is it worth my life to attempt to cross the bridge? The fog prevents a clear view of the other side, and a gust of wind starts to make the bridge sway. How far is it? When will the swaying stop? The only question the physicist can be certain of is that there exists something on the other side that the rope is tied to.

This great divide is analogous to that connecting between General Relativity and Quantum Mechanics. For almost 100 years we've stood at the edge of the divide and wondered how to fill the gap between the two cliffs. We believed that if we built up vertically high enough on one side that it would eventually make it over to the other, and we have yet to see anyone jump. We do this because we do not trust the rope bridge, we don't understand how it was built or what it is able to carry. We say that the bridge is “a spooky action at a distance” because the first rope was thrown as an accident. Einstein believed he could throw a hook into the fog and watch it fall in the crevice to prove that there was no other side but was shocked when his hook hit something.

Einstein was both the founder of General Relativity, and an initial contributor to Quantum Mechanics with his paper on the Photoelectric Effect. However, as Quantum Mechanics progressed, he started to have issues with the lack of determinism and non-locality that would violate the speed of light. His most important criticism was the EPR paradox.

In 1935, Einstein, Podolsky, and Rosen (the EPR that is known today) distilled their issue(s) with Quantum Mechanics into a paradox with unacceptable conclusions [1]. Einstein imagined a pair of particles that are created to have equal and opposite position and momentum components. If these two particles are separated by a large distance, one particle can be measured for its position, and the other can be measured for its momentum. One can deduce the corresponding position and momentum of the opposite particle, and then finally we would have the complete measurement for both particles. However, the Uncertainty Principle limits the knowledge that one can obtain of both the position and momentum, therefore measurement of one particle would instantaneously affect the other particle despite the large distance, violating causality. This would suggest that either Quantum Mechanics is incomplete, or an action in one “localized” region could have an effect on another “localized” region before the signal of the action could travel, and in Einstein’s words, “no reasonable definition of reality could be expected to permit this” [1].

Schrödinger solved the paradox by seeing that the two particles are not independent in their wavefunctions. In his paper, "Probability Relations between Separated Systems", he explained that after interaction, the two particles have a shared wavefunction that can stretch over any distance [2]. He came up with the term Entanglement to describe the state of a wave function after two independent wavefunctions have interacted. On entanglement, he wrote "I would not call that one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought. By the interaction the two representatives (or wavefunctions) have become entangled. To disentangle them we must gather further information by experiment" [2]. Einstein's paradox was resolved, but he could not overcome the non-local nature of quantum mechanics which violates the locality constraint of general relativity.

Einstein would come to question locality and causality, two primary assertions in General Relativity. Locality is the idea that signals of events travel at the speed of light, and causality is the idea that these signals have effects on distant particles. The only way Einstein could integrate Entanglement into General Relativity is to create a hole in space-time that connects two non-local regions[1]. This is called the Einstein Rosen Bridge, and it is only possible with sufficient negative energy [3]. In science fiction, it's known as a wormhole. While still a very uncomfortable idea, entanglement now has two descriptions between General Relativity and Quantum Mechanics that agree on the experimental result. It is the single rope that is suspended between the two cliffs. Einstein walked the tightrope that he had created and spent the rest of his life trying to create a Grand Unified Theory but did not succeed.

David Bohm was one of next physicists to cross the rope from the other direction. One of Einstein's initial problems with Quantum Mechanics was the complex nature of particles involving imaginary numbers in Schrödinger's Equation, as well as the lack of determinism. David Bohm created Bohmian Mechanics, a realist interpretation of Quantum Mechanics similar to Louis De Broglie's Pilot Wave Theory [4]. Bohmian Mechanics utilizes hidden variables as the lack of knowledge of the initial positions of particles. The apparatus of an experiment creates a wave and the wave tells the particle where to go. Since it is very similar in nature to the relativistic concept of matter telling space how to curve, and space telling matter how to move, Bohm had thought that Einstein would love the theory. However, Einstein rejected the non-local nature of his theory, and didn't support Bohm when he was a suspected communist during the era of McCarthyism. Bohm had to flee to Brazil to avoid prison. In the public eye, it took years for him to overcome this reputation, but his theory caught the attention of a particular physicist John Bell.

Given the influence that John Bell had on the entire physics community, it's more accurate to say that he levitated over the great divide. In one of the most cited works of all time, "On the Einstein Podolsky Rosen Paradox", John Bell took the arguments of General Relativity and Quantum Mechanics and put them next to each other [5]. He utilized classical probability theory and the new Bohmian probability theory, and created a set of constraints that could be used to determine whether the fundamental nature of particles was Quantum Mechanical or relativistic. He recognized that there are two sides of the rope, and he found exactly what makes the two sides different. Bell's Inequality and derivatives thereof are the expectation values of experiments for both local and non-local variables. In crossing, he tied the second rope between the two cliffs, giving entanglement twice the strength that it had before.

One of the first physicists to take the Bell Inequalities seriously was John Clauser. Although Bell's inequalities were experimentally impossible to test, a new set of inequalities could be formulated using Bell's which could be tested. The first testable inequality is known as the CHSH inequality, after its creators John Clauser, Michael Horne, Abner Shimony, and Richard Holt, and today there are countless inequalities that could be created for different experiments [6]. After creating the new inequalities, John Clauser created the first experimental test of them. The experiment took a beam of Calcium and excited the atoms in the crystal to a high energy level [7]. When an atom returned to the ground state, it would release two photons of different wavelengths in opposite directions. These photons would travel through polarization filters and hit detectors on the other side. If the polarization filters are aligned, either both detectors will see the photons, or neither of them will see. The polarization filters could be rotated, and the correlations would depend on the relative angle between the filters. The results showed that it was consistent with non-locality, and this was the first experimental proof of violating Bell's Inequality [7]. John Clauser is responsible for adding the wooden planks that turn a tightrope walk into a real bridge. Although the bridge is scary, it became more inviting for people to walk over, and even ride over.

Stephen Hawking considered the behavior of Quantum Mechanics around the boundary of a black hole. In Quantum Field Theory, there is an inherent energy fluctuation in the vacuum of space due to the Heisenberg uncertainty principle. Pairs of particles and antiparticles are able to spontaneously be created as long as they come back together and annihilate each other in a short period of time. These particles are entangled, as they share a wavefunction. When these pairs of particles are created at the Schwarzschild radius, one particle will fall into the black hole, while the other goes out to infinity. The particle that escaped is known as Hawking Radiation, and this takes energy away from the black hole, which decreases its mass [8]. Although Hawking's initial arguments were driven by thermodynamics, the solution came about through consideration of entangled particles, and he was able to reconcile the boundary between General Relativity and Quantum Mechanics. His crossing is a sign of the strength of the bridge, and the bridge continues to this day to be crossed by and improved upon.

Over the past 30 years, there has been a new wave of physicists crossing the bridge. This comes from the implementation and application of Quantum Computers. A common fact about quantum computing is that the size of the computation space increases exponentially with a linear increase in physical size. This exponential increase is strictly due to entanglement. Imagine changing a bit in a classical computer from 0 to 1, only that single bit is affected. In a system of entangled qubits, changing a single qubit changes the state of all the qubits. The power of entangled qubits is most exemplified by Shor's Factorization Algorithm, created by Peter Shor. In a normal factorization algorithm, a classical computer tests factors one at a time until the solution is found. In paraphrasing Shor's Algorithm, a system of entangled qubits represents all possible factors at once, and the factors which aren't correct destructively interfere while the correct factors constructively interfere [9]. This algorithm is so powerful that with a large enough quantum computer it breaks RSA encryption, a cryptographic algorithm that secures our communication over the internet. However, once again, entanglement offers a solution in the form of quantum teleportation, and a new era of cryptography guaranteed by the laws of physics will protect us.

As a young physicist approaching this new era of technology, I have chosen to embrace entanglement and try to understand as much as I can, despite its confusing, counterintuitive nature. We can learn lessons from history by looking at those who came before us to give us the confidence to cross the bridge. Suspend your disbelief, lean into entanglement, and start applying entangled thinking to solve modern problems. And finally, let's rebrand entanglement as "correlated action at a distance", because entanglement is not meant to scare us, it is meant to connect us all.

References

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Notes

[1] The correspondence between the EPR paradox and the Einstein Rosen Bridge was not explicitly put forward by Einstein but is a conjecture by Leonard Susskind and Juan Maldacena. Experimental evidence of this is lacking, but the historical evidence is that both papers were written within two months of each other, by two of the same authors, and both are discussions of connections between non-local regions, one as a solution in Quantum Mechanics, and the other as a solution in General Relativity. One can only speculate that Einstein considered them the same thing.