SAMPLE

Quantum Entanglement

Spooky Action at a Distance

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Introduction

Quantum entanglement is the phenomenon in which the quantum state of each particle in a group cannot be described independently of the state of the others, even when the particles are separated by a large distance. The topic of quantum entanglement is at the heart of the disparity between classical physics and quantum physics: entanglement is a primary feature of quantum mechanics not present in classical mechanics.

Measurements of physical properties such as position, momentum, spin, and polarization performed on entangled particles can, in some cases, be found to be perfectly correlated.

For example, if a pair of entangled particles is generated such that their total spin is known to be zero, and one particle is found to have clockwise spin on a first axis, then the spin of the other particle, measured on the same axis, is found to be anticlockwise.

This behavior gives rise to seemingly paradoxical effects: any measurement of a particle's properties results in an apparent and irreversible wave function collapse of that particle and changes the original quantum state. With entangled particles, such measurements affect the entangled system as a whole.

Such phenomena were the subject of a 1935 paper by Albert Einstein, Boris Podolsky, and Nathan Rosen, and several papers by Erwin Schrödinger shortly thereafter, describing what came to be known as the EPR paradox.

Einstein and others considered such behavior impossible, as it violated the local realism view of causality and argued that the accepted formulation of quantum mechanics must therefore be incomplete. Later, the counterintuitive predictions of quantum mechanics were verified in tests where polarization or spin of entangled particles were measured at separate locations, statistically violating Bell's inequality.

This established that the correlations produced from quantum entanglement cannot be explained in terms of local hidden variables.

Entanglement can produce statistical correlations between events in widely separated places, but it cannot be used for faster-than-light communication. Quantum entanglement has been demonstrated experimentally with photons, electrons, top quarks, molecules and even small diamonds. The use of quantum entanglement in communication and computation is an active area of research and development.

Albert Einstein and Niels Bohr engaged in a long-running collegial dispute over the interpretation of quantum mechanics, now known as the Bohr- Einstein debates.

During these debates, Einstein introduced a thought experiment involving a box that emits a photon. He noted that the experimenter's choice of which measurement to make on the box would change what can be predicted about the photon, even when the photon is very far away. This argument, which Einstein had formulated by 1931, was an early recognition of what would later be called entanglement.

That same year, Hermann Weyl observed in his textbook on group theory and quantum mechanics that quantum systems composed of multiple interacting parts exhibit a kind of Gestalt, in which "the whole is greater than the sum of its parts". In 1932, Erwin Schrödinger derived the defining equations of quantum entanglement but left them unpublished.

In 1935, Grete Hermann studied the mathematics of an electron interacting with a photon and noted the phenomenon that would later be called entanglement.

The Hilbert space of the composite system is the tensor product

If the first system is in state

States of the composite system that can be represented in this form are called separable states, or product states. Fix a basis

By writing the density matrices as sums of pure ensembles and expanding, we may assume without loss of generality that

As indicated above, in general there is no way to associate a pure state to the component system A. Let

If Alice and Bob share an entangled state, Alice can tell Bob over a telephone call how to reproduce a quantum state

Instead of considering transformations of single copies of a state (like

All three sets are non-empty. In classical information theory H, the Shannon entropy, is associated to a probability distribution, Since Alice's measurement necessarily erases the quantum state of the system in her lab, the state

An example for a three-qubit system is the Greenberger-Horne-Zeilinger (GHZ) state, Another three-qubit example is the W state:

Tracing out any one of the three qubits turns the GHZ state into a separable state, whereas the result of tracing over any of the three qubits in the W state

is still entangled.

. If the first system is in state

, the state of the composite system is

The most general state in HA ⊗ HB is of the form

This state is separable if there exist vectors

It is inseparable if for any vectors

..Entanglement is often introduced as quantum mechanics at its strangest, but strangeness is not its most important quality. Its importance is operational. Entangled systems provide correlations that no theory built from local, pre-existing properties can reproduce, and those correlations can be measured, transmitted through protocols, and turned into working technologies. The subject therefore joins three kinds of inquiry that are usually kept apart: a foundational question about what reality contains, an experimental question about what laboratories can distinguish, and an engineering question about what unusual correlations can accomplish. This book follows all three. It treats the paradoxes historically, the formal ideas in plain prose, and the applications as concrete procedures rather than slogans. The goal is not to make the phenomenon less surprising. It is to make the surprise precise enough to use.

The scale of the subject is worth stating at the outset: entanglement has moved, in ninety years, from a philosophical objection into the operating principle of a global engineering race, the resource behind quantum cryptography, quantum teleportation, and every serious design for a quantum computer. This book follows that whole arc, from the 1935 paper that named the puzzle, through the laboratory decades that turned argument into experiment, to the present day, in which the correlations Einstein distrusted are measured routinely, shipped through fiber and satellite, and taught to students as the working vocabulary of a new technology.

Chapter 1: The Discovery of Quantum Entanglement

Their thought experiment considered two systems that interact and then separate, and they argued that, afterward, quantum mechanics could not describe the two systems individually. Shortly after this paper appeared, Erwin

Schrödinger wrote a letter to Einstein in German in which he used the word Verschränkung (translated by himself as entanglement) to describe situations like that of the EPR scenario.

Schrödinger followed up with a full paper defining and discussing the notion of entanglement, saying "I would not call [entanglement] one but rather the characteristic trait of quantum mechanics, the one that enforces its entire departure from classical lines of thought." Like Einstein, Schrödinger was dissatisfied with the concept of entanglement, because it seemed to violate the speed limit on the transmission of information implicit in the theory of relativity.

Einstein later disparaged quantum mechanics for seemingly exhibiting "spukhafte Fernwirkung", or "spooky action at a distance", meaning the acquisition of a value of a property at one location resulting from a measurement at a distant location. In 1946, John Archibald Wheeler suggested studying the polarization of pairs of gamma-ray photons produced by electron-positron annihilation.

Chien-Shiung Wu and Irving Shaknov carried out this experiment in 1949, thereby demonstrating that the entangled particle pairs considered by EPR could be created in the laboratory.

Despite Schrödinger's claim of its importance, little work on entanglement was published for decades after his paper was published. In 1964 John S. Bell demonstrated an upper limit, seen in Bell's inequality, regarding the strength of correlations that can be produced in any theory obeying local realism, and showed that quantum theory predicts violations of this limit for certain entangled systems.

His inequality is experimentally testable, and there have been numerous relevant experiments, starting with the pioneering work of Stuart Freedman and John Clauser in 1972, and Alain Aspect's experiments in 1982. While Bell actively discouraged students from pursuing work like his as too esoteric, after a talk at Oxford a student named Artur Ekert suggested that the violation of a Bell inequality could be used as a resource for communication.

Ekert followed up by publishing a quantum key distribution protocol called E91 based on it.

In 1992, the entanglement concept was leveraged to propose quantum teleportation, an effect that was realized experimentally in 1997. Beginning in the mid-1990s, Anton Zeilinger used the generation of entanglement via parametric down-conversion to develop entanglement swapping and demonstrate quantum cryptography with entangled photons.

In 2022, the Nobel committee in Stockholm gave its physics prize to Aspect, Clauser, and Zeilinger, citing "experiments with entangled photons, establishing the violation of Bell inequalities and pioneering quantum information science".

Just as energy is a resource that facilitates mechanical operations, entanglement is a resource that facilitates performing tasks that involve communication and computation. The mathematical definition of entanglement can be paraphrased as saying that maximal knowledge about the whole of a system does not imply maximal knowledge about the individual parts of that system.

If the quantum state that describes a pair of particles is entangled, then the results of measurements upon one half of the pair can be strongly correlated with the results of measurements upon the other. However, entanglement is not the same as "correlation" as understood in classical probability theory and in daily life.

Instead, entanglement can be thought of as potential correlation that can be used to generate actual correlation in an appropriate experiment.

The correlations generated from an entangled quantum state cannot in general be replicated by classical probability. An example of entanglement is a subatomic particle that decays into an entangled pair of other particles.

The decay events obey the various conservation laws, and as a result, the measurement outcomes of one daughter particle must be highly correlated with the measurement outcomes of the other daughter particle (so that the total momenta, angular momenta, energy, and so forth remains roughly the same before and after this process).

For instance, a spin-zero particle could decay into a pair of spin-1/2 particles. If there is no orbital angular momentum, the total spin angular momentum after this decay must be zero (by the conservation of angular momentum). Whenever the first particle is measured to be spin up on some axis, the other, when measured on the same axis, is always found to be spin down.

This is called the spin anti-correlated case and the pair is said to be in the singlet state.

Perfect anti-correlations like this could be explained by "hidden variables" within the particles. For example, we could hypothesize that the particles are made in pairs such that one carries a value of "up" while the other carries a value of "down". Then, knowing the result of the spin measurement upon one particle, we could predict that the other will have the opposite value.

Bell illustrated this with a story about a colleague, Bertlmann, who always wore socks with mismatching colors.

Quantum systems can become entangled through various types of interactions.

For some ways in which entanglement may be achieved for experimental purposes, see the section below on methods. Entanglement is broken when the entangled particles decohere through interaction with the environment; for example, when a measurement is made. In more detail, this process involves the particles becoming entangled with the environment, as a consequence of which, the quantum state describing the particles themselves is no longer entangled.

Mathematically, an entangled system can be defined to be one whose quantum state cannot be factored as a product of states of its local constituents; that is to say, they are not individual particles but are an inseparable whole. When entanglement is present, one constituent cannot be fully described without considering the other(s).

The state of a composite system is always expressible as a sum, or superposition, of products of states of local constituents; it is entangled if this sum cannot be written as a single product term. The singlet state described above is the basis for one version of the EPR paradox. In this variant, introduced by David Bohm, a source emits particles and sends them in opposite directions.

The state describing each pair is entangled.

The argument that made entanglement famous began in 1935. Einstein, Boris Podolsky, and Nathan Rosen asked whether quantum mechanics could be complete when it allowed a measurement on one member of a separated pair to fix what could be predicted about the other. Their conclusion favored hidden information, properties carried by the particles but omitted by the wavefunction. Erwin Schrödinger answered in the same year, coined the German term that became entanglement, and identified the phenomenon not

as a minor oddity but as the characteristic feature of quantum theory. The disagreement then waited nearly thirty years for a test. John Bell's 1964 inequality transformed the philosophical dispute into an experimental choice: local hidden-variable theories obey one numerical limit, while quantum entanglement can violate it. That transformation, from interpretation to number, is the decisive discovery in the subject's history.

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ABOUT THE AUTHOR

Aira Astralis is a science writer specializing in astronomy and space exploration. Her work spans the full breadth of humanity's relationship with the cosmos -- from the earliest naked-eye observations to the engineering marvels of modern space missions.

Her books are built on a foundation of primary sources: peer-reviewed research, mission archives, and direct engagement with the scientific community. She writes for readers who want to understand not just what we know about the universe, but how we came to know it.

She believes that the most important frontier is not out there but in the gap between what scientists discover and what the public understands. Her books exist to close that gap.