NOBEL PRIZE

Pioneering Quantum Physicists Win Nobel Prize in Physics

By CHARLIE WOOD

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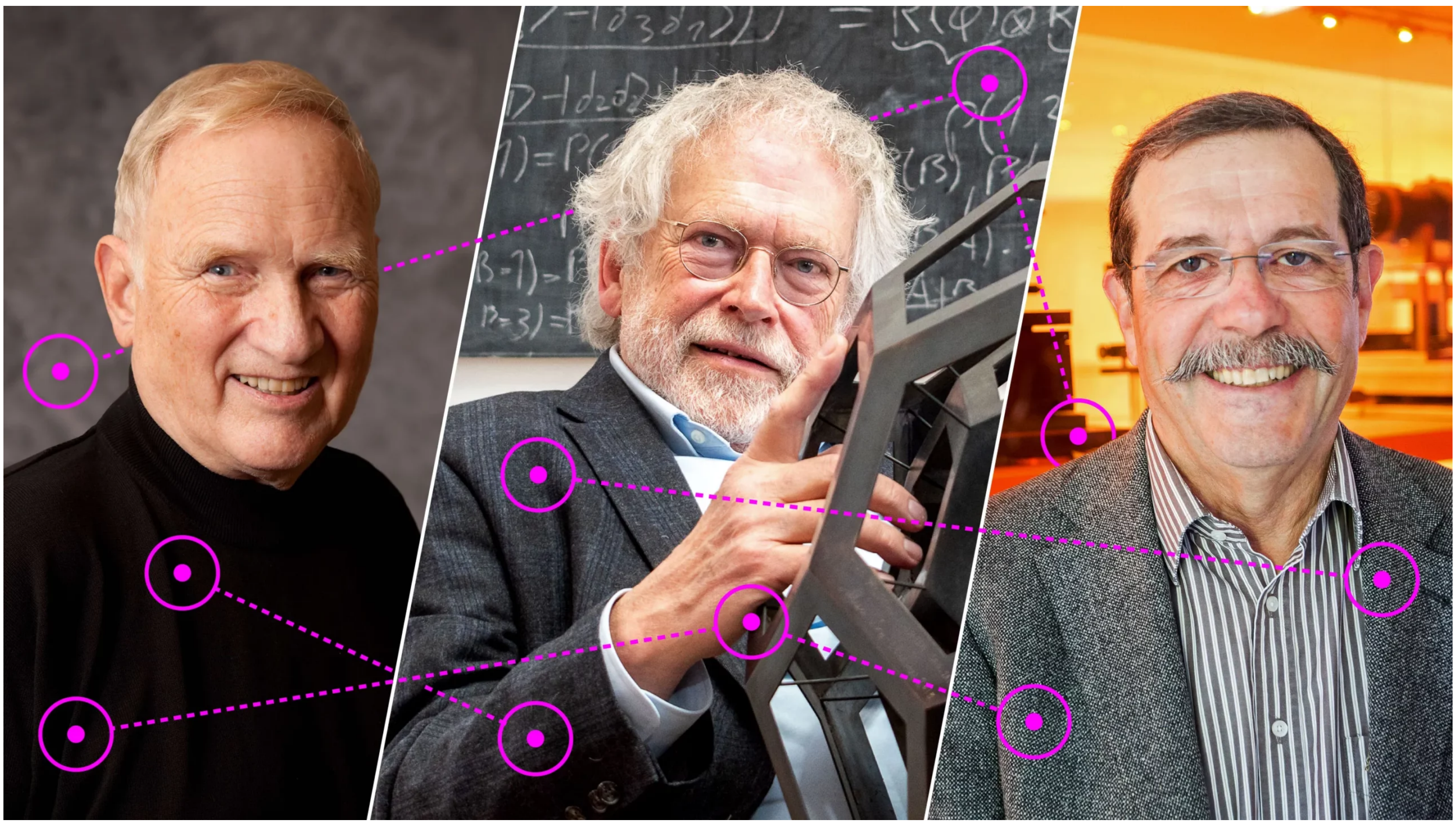
Alain Aspect, John Clauser and Anton Zeilinger have won the 2022 Nobel Prize in Physics for groundbreaking experiments with entangled particles.



From left: John Clauser, Anton Zeilinger and Alain Aspect.

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(left) Courtesy of John Clauser; Jacqueline Godany; Ecole polytechnique Université Paris-Saclay

The physicists Alain Aspect, John Clauser and Anton Zeilinger have won the 2022 Nobel Prize in Physics for experiments that proved the profoundly strange quantum nature of reality. Their experiments collectively established the existence of a bizarre quantum phenomenon known as entanglement, where two widely separated particles appear to share information despite having no conceivable way of communicating.

Entanglement lay at the heart of a fiery clash in the 1930s between physics titans Albert Einstein on the one hand and Niels Bohr and Erwin Schrödinger on the other about how the universe operates at a fundamental level. Einstein believed all aspects of reality should have a concrete and fully knowable existence. All objects — from the moon to a photon of light — should have precisely defined properties that can be discovered through measurement. Bohr, Schrödinger and other proponents of the nascent quantum mechanics, however, were finding that reality appeared to be fundamentally uncertain; a particle does not possess certain properties until the moment of measurement.

Entanglement emerged as a decisive way to distinguish between these two possible versions of reality. The physicist John Bell proposed a decisive thought experiment that was later realized in various experimental forms by Aspect and Clauser. The work proved Schrödinger right. Quantum mechanics was the operating system of the universe.

"I would not call entanglement 'one,' but rather 'the' trait of quantum mechanics," Thors Hans Hansson, a member of the Nobel committee, quoted Schrödinger as writing in 1935. He observed, "The experiments performed by Clauser and Aspect opened the eyes of the physics community to the depth of Schrödinger's statement, and provided tools for creating and manipulating and measuring states of particles that are entangled although they are far way."

In addition to its paradigm-shattering philosophical implications, entanglement is now poised to power an emerging wave of quantum technologies. Zeilinger has been at the forefront of the field, developing techniques that use entanglement to achieve astounding feats of quantum networking, teleportation and cryptography.

"Quantum information science is a vibrant and rapidly developing field. It has broad potential implications in areas such as secure information transfer, quantum computing, and sensing technology," said Eva Olsson, another member of the committee. "Its predictions have opened doors to another world, and it has also shaken the very foundations of how we interpret measurements."

What is quantum entanglement?

Two particles are entangled when together they form one quantum system, regardless of the distance between them.

To understand this kind of quantum connection, consider two electrons. Electrons have a quantum property called spin, which, when measured, can take one of two values, referred to as "up" or "down." Measuring the spin of each electron is like tossing a coin: It will randomly come out up or down.

Now imagine that two physicists, Alain and John, each receive a series of coins in the mail. As each pair of coins arrives, the physicists flip them at the same time. Alain might get the sequence heads, tails, tails, heads, tails. And John might get heads, heads, tails, tails, tails. The outcome of Alain's and John's coin tosses will have nothing to do with each other.

But if they repeat this experiment with a series of entangled electrons instead of coins, they'll get a strange result: Each time Alain measures an electron that's spin-up, John will find that his corresponding half of the electron pair comes out spin-down, and vice versa. The two acts of measurement are connected, almost as if flipping one coin could send out a signal that instantaneously ensured the proper outcome of its distant partner at the precise moment of measurement.

It was Einstein, along with Boris Podolsky and Nathan Rosen, who first described quantum entanglement in a now-infamous 1935 paper. The phenomenon, which Einstein disparagingly dubbed "spooky action at a distance," was an unavoidable consequence of the nascent theory of quantum mechanics. Einstein suspected that entanglement would prove the death knell of quantum mechanics because it seemed to fly in the face of a central tenet of relativity — that no information could travel faster than the speed of light. No measurement of one electron should be able to instantly influence a measurement in some distant place.

Instead, their paper would lay the foundation for a complete rethinking of reality and a radical new field of research.

How do you measure entanglement?

By the 1930s, it was clear that Bohr, Schrödinger and the other quantum pioneers were onto something; the theory described experiments with atoms and subatomic particles more accurately than any other theory. The debate was how far one could trust it.

Einstein, for instance, held out hope that the bizarre theory was just a steppingstone on the way to a more complete picture that would philosophically align with classical physics. He suspected that two entangled electrons took on opposing spins because some "hidden variable" caused their spins to point in opposite directions in the first place. In other words, what looked like a random measurement outcome in quantum mechanics was actually the result of some as yet unappreciated deterministic description that created an illusory connection between the particles.

In 1964, John Stewart Bell proposed an experiment that could settle the debate. The details are rather involved, but the general idea was for two physicists to measure the spins of entangled particles along different axes: not just up and down but sometimes, randomly, left and right or in other directions. If Einstein was right, and the particles secretly had predetermined spins all along, then the act of switching the axis of measurement should have no effect on the outcome. Bell calculated that if the universe was truly quantum mechanical, and entanglement was as spooky as it seemed, the axis-switching would lead to correlated spin measurements more often than would be possible in classical theories like relativity.

"John Bell translated the philosophical debate into science and provided testable predictions that launched experimental work," said Olsson.

TIMELINE

1935

Albert Einstein, Boris Podolsky and Nathan Rosen argue that quantum physics misses some “hidden variables” that would explain apparent quantum paradoxes.

1964

John Bell devises a thought experiment that suggests that the states of entangled particles are too correlated to be explained by hidden variables.

1969

The American physicist **John Clauser** and colleagues refine Bell’s theorem and propose an experiment to test it against real-world data.

1972

Clauser and a colleague observe a violation of Bell's inequality for the first time in an experiment.

1982

Alain Aspect of France carries out a series of experiments that confirm the violations of Bell’s theorem, but a few loopholes remain.

2017

The Austrian physicist **Anton**

Zeilinger and colleagues demonstrate a loophole-free test that finally closes the door on Einstein, Podolsky and Rosen's hidden-variables theory.

2022

The Nobel Prize in Physics is awarded to Clauser, Aspect and Zeilinger for their explorations of quantum entanglement.

Merrill Sherman/Quanta Magazine

Who performed Bell's experiment?

John Clauser, of Lawrence Berkeley National Laboratory and the University of California, Berkeley, and Stuart Freedman, a graduate student, were the first to take Bell's experiment from the page into the lab. Clauser realized that the experiment would be more feasible if it involved not spinning electrons but polarized photons — particles of light. Like the spin direction of an electron, the polarization of a photon can take on one of two values relative to the orientation of a filter. Polarized sunglasses, for example, block photons that are polarized one way and let in photons polarized in the other manner.

Initially, physicists including Richard Feynman discouraged Clauser from pursuing the experiment, arguing that quantum mechanics needed no further experimental proof. But Bell personally encouraged Clauser to see the research through, and in 1972 Clauser and Freedman succeeded in realizing Bell's experiment. They generated pairs of entangled photons and used lenses to measure their polarization directions. Unsure what he would find, Clauser had placed a $2 bet that his experiment would prove Einstein right. To his surprise, his results vindicated Bell's prediction over Einstein's. The photons' states appeared correlated in a way that precluded any hidden-variable theory. Clauser's lost bet was a huge victory for quantum mechanics.

"I was very sad to see that my own experiment had proven Einstein wrong," he said years later in an interview.

But Clauser's evidence still wasn't ironclad. His experiment used fixed orientations of the lenses, allowing for a loophole: If a hidden variable that coordinates the photons' polarizations somehow depends on the experimental positioning of the lenses, Einstein could yet be right.

Enter Alain Aspect. He carried out a series of increasingly stringent Bell tests in Paris, culminating in a devilishly sophisticated experiment in 1982. In that test, the orientation of the lenses would randomly change during the billionths of a second that the photons spent flying from the emitter to the lens. In this way, the initial lens configuration was erased and could have no influence on any secret process setting the polarization at the moment of their emission. Once more, the experiment found in favor of Bell and quantum mechanics.

Only the slimmest of loopholes remained. Could a secret and nonrandom process that was somehow set in motion at the beginning of the experiment determine how the lenses would update? Anton Zeilinger's research at the University of Vienna further narrowed this remaining sliver of doubt. In a 2017 experiment, he led a team that used the colors of photons emitted from distant stars hundreds of years ago to determine the settings of the experiment. If some cosmic conspiracy was creating the illusion of entanglement, it would have had to begin centuries before the births of the experimenters.

Some physicists still float theories that maintain Einstein's dream. Superdeterminism, for instance, holds that every detail of the universe's fate, down to the spin and polarization of every last particle, was completely fixed at the Big Bang — before the stars (or Zeilinger's cosmic Bell test) formed.

But most researchers take the work of Bell, Clauser, Aspect, Zeilinger and their teams at face value. Entanglement is what it seems: The pair of particles is one unified system. For each individual particle, properties like spin and polarization really are undefined until the moment of measurement. In other words, reality has no fixed and predetermined state until you measure it. It's a dramatic conclusion that most researchers accept but still struggle to fully grasp.

"The very fundamental question — what does this really mean in a basic way? — is unanswered, and is an avenue for new research," said Zeilinger.

What is entanglement good for?

In the nearly 90 years since Einstein tried to kill quantum mechanics by highlighting the absurdity of entanglement, the phenomenon has become much more than fodder for philosophical debates. It's one of the main engines driving the booming field of quantum information science.

"Physicists are now starting to understand that entanglement and Bell pairs [are] a quantum resource that you can use to achieve amazing new things," said Hansson.

Zeilinger is one of the central figures leading the effort to work technological miracles with entanglement. In 1997, he and his colleagues were the first to pull off a feat known as quantum teleportation, which uses a precise protocol of measurements on entangled particles to transfer the polarization direction of one particle over to another without the researchers ever learning the polarization direction that was transported. The technique may come to play a crucial role in quantum computing. "It is not like in the *Star Trek* films or whatever, transporting something — certainly not a person — over some distance," Zeilinger said by phone during the Nobel announcement. "The point is, using entanglement, you can transfer all the information that is carried by an object over to another place, where the object is, so to speak, reconstituted."

Zeilinger also developed a procedure called entanglement swapping, involving the emission of two entangled Bell pairs, for a total of four particles. When you perform a particular measurement on two of the particles that are not entangled, the remaining two become entangled with each other. Swapping entanglement from particle to particle in this way could help link nodes in a quantum communication network. In a landmark 1998 publication, Zeilinger and his collaborators demonstrated the ability to swap entanglement between photons that had never been in contact with each other.

In recent years, such technologies have left the lab and entered the real world. Jian-Wei Pan, a former student of Zeilinger's, heads up a Chinese group that launched a satellite named Micius in 2016. Micius beamed pairs of photons to labs in China that were separated by more than 1,000 kilometers. The group's measurements proved that entanglement had survived the journey. Pan's group later worked with Zeilinger's group in Austria to distribute pairs of entangled particles across the Eurasian continent. This long-distance entanglement distributed a secret message, a so-called quantum key, which gets destroyed by any attempt to intercept the information. The demonstration paves the way for essentially unbreakable cryptography, which will be guaranteed by the thoroughly tested fundamentals of quantum mechanics.

Who won the Nobel Prize in Physics in recent years?

Last year, Syukuro Manabe and Klaus Hasselmann were honored for their work that led to reliable predictions of the effects of climate change; they shared the Nobel with Giorgio Parisi, who performed trailblazing studies of chaotic physical systems. In 2020, Roger Penrose, Reinhard Genzel and Andrea Ghez received the prize for their studies of black holes. Half of the 2019 Nobel went to the astronomers Michel Mayor and Didier Queloz for their 1995 discovery of a Jupiter-like planet orbiting a nearby star, and the other half went to the cosmologist James Peebles for work exploring the structure of the universe. In 2018, three laser physicists were honored: Arthur Ashkin, who took half of the prize for inventing "optical tweezers," and Gérard Mourou and Donna Strickland for their work on ultra-short laser pulses. And the 2017 Nobel went to the American physicists Rainer Weiss, Kip Thorne and Barry Barish, three of the architects of the experiment that confirmed the existence of gravitational waves.