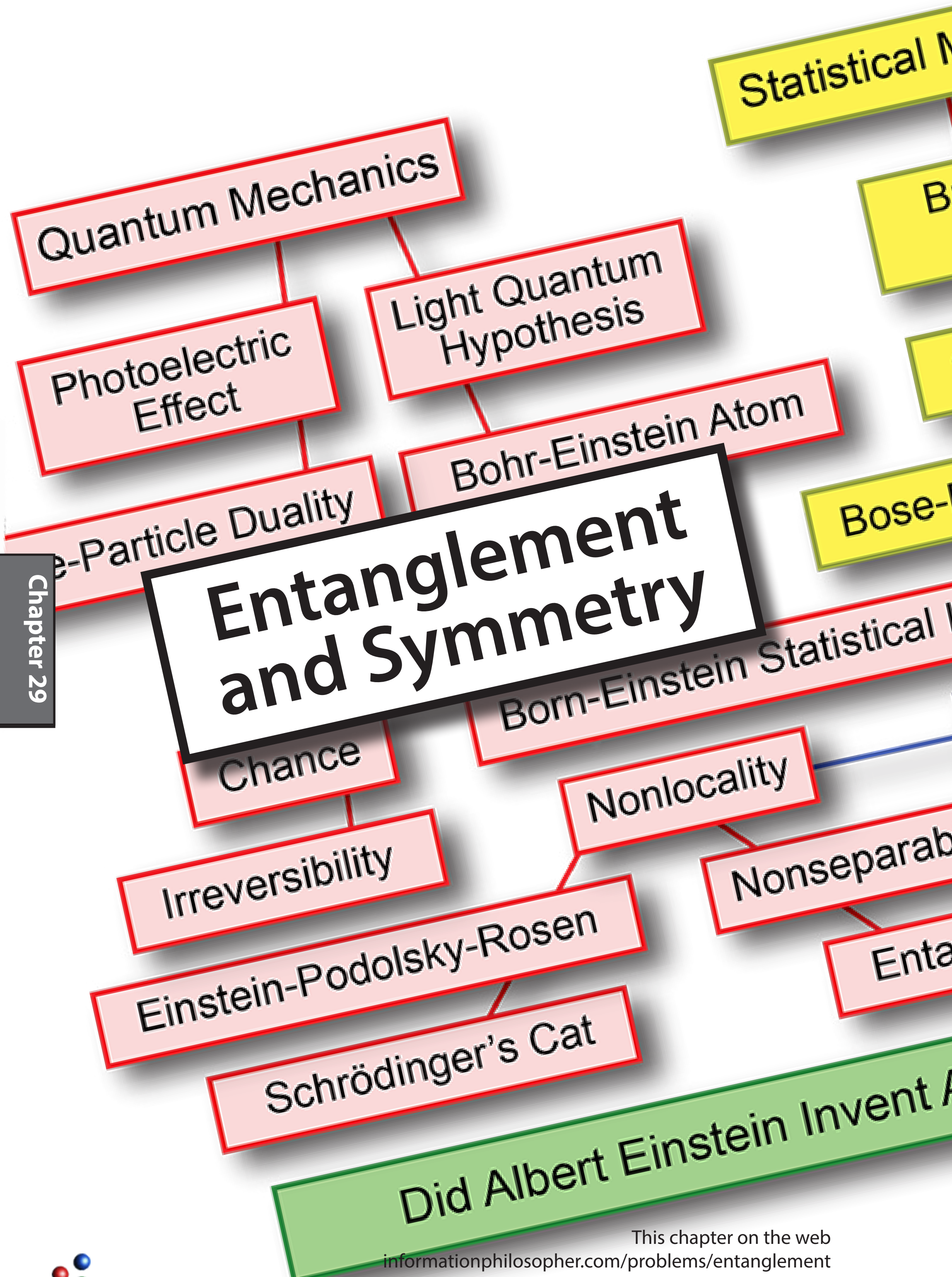
Chapter 29

Entanglement and Symmetry



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Entanglement and Symmetry

In his pioneering work on special and general relativity, Einstein's greatest work came from his use of fundamental "principles" to derive his new results. In special relativity, it was the principle that light has the same speed in all frames of reference. In general relativity, it was his equivalence principle, that an observer cannot distinguish between an accelerated frame and the force of gravity.

Each of these principles emerges from an underlying symmetry that produces an invariant quantity or a conservation law.

The speed of light is an invariant. The laws of physics are the same at different places in space-time. Otherwise we couldn't repeat experiments everywhere and discover the laws of nature.

Einstein discovered symmetries that helped him reformulate Maxwell's laws of electromagnetic fields. A few years later Emmy Noether (often described as the most important female mathematician) made a profound contribution to theoretical physics with her theorem on the fundamental relationship between symmetry and conservation principles.

> *For any property of a physical system that is symmetric, there is a corresponding conservation law.*

For example, if a physical system is symmetric under rotations, its angular momentum is conserved. If symmetric in time, energy is conserved. If symmetric in space, momentum is conserved.

Noether's theorem allows physicists to gain powerful insights into any general theory in physics, by just analyzing the various transformations that would make the form of the laws involved invariant. No one understood the importance of these invariance principles better than Einstein. Nevertheless, Einstein introduced an odd asymmetry where none belongs in his EPR analysis of the behavior of two "entangled" particles.

Einstein's Introduction of a False Asymmetry?

Almost every presentation of the EPR paradox and descriptions of entanglement begins with something like "Alice observes one particle..." and concludes with the question "How does the second particle get the information needed so that Bob's later measurements correlate perfectly with Alice's?"

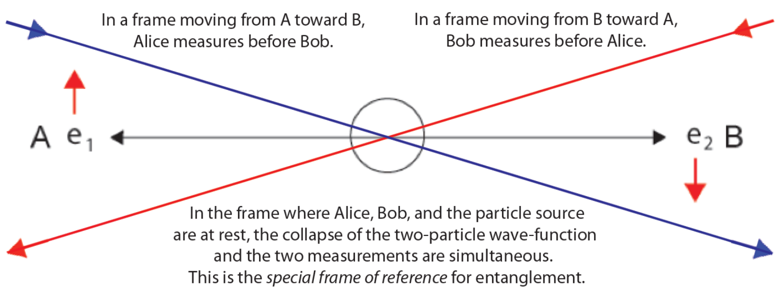
There is a fundamental *asymmetry* in this framing of the EPR experiment. It is a surprise that Einstein, who was so good at seeing deep symmetries, did not consider how to remove the asymmetry.

Consider this reframing: Alice's measurement collapses the two-particle wave function Ψ_{12}. The two indistinguishable particles simultaneously appear at locations in a space-like separation. The frame of reference in which the source of the two entangled particles and the two experimenters are at rest is a *special frame* in the following sense. It is the frame in which their appearance is *simultaneous*. In this frame, the experiment is *symmetric*.

As Einstein knew very well, there are frames of reference moving with respect to the laboratory frame of the two observers in which the time order of the events can be reversed. In some moving frames Alice measures first, in others Bob measures first.

Einstein also knows well that two events in spacelike separation can have no causal influence on one another. They are not in one another's "light cone." No signals communicate between them.

If there is a *special* frame of reference (not a *preferred* frame in the relativistic sense), surely it is the one in which the origin of the two entangled particles is at rest.



Assuming that Alice and Bob are also at rest in this special frame and equidistant from the origin, we arrive at the simple picture in which any measurement that causes the two-particle wave function to collapse makes both particles appear simultaneously at determinate places with fully correlated properties (just the values that are needed to conserve energy, momentum, angular momentum, and spin).

Instead of the one particle making an appearance in Einstein's original case of nonlocality, in the two-particle case, when either particle is measured - or better, when the wave function is disturbed? - both particles appear.

The two-particle wave function splits into two single-particle wave functions.

$\Psi_{12} => \Psi_1 \Psi_2$

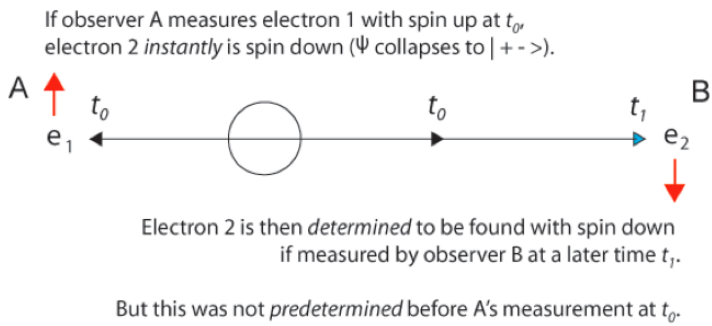
At this moment, the two-particle wave function decoheres (no longer shows interference properties), the particles are disentangled,

We know instantly those properties of the other particle that satisfy the conservation laws, including its location equidistant from, but on the opposite side of, the source, along with its other properties such as the spin, which must be equal and opposite to add up to the original spin = zero, for example.

When Alice detects the particle at t_0 (with say spin up), at that instant the other particle also becomes determinate (with spin down) at the same distance on the other side of the origin. The particles separate at t_0. Further measures of either particle will have no effect on the other!

Note that should Bob have measured before t_0, his would be the "first" measurement that causes the two-particle wave function to decohere and the particles to disentangle and finally separate.

We can also ask what happens if Bob is not at the same distance from the origin as Alice. This introduces a positional asymmetry. But there is still no time asymmetry from the point of view of the two-particle wave function collapse at t_0.



What Did Einstein See? The Special Frame?

Remember Einstein's 1933 question to Leon Rosenfeld, "How can the final state of the second particle be influenced by a measurement performed on the first..."[1] Why did Einstein see something unusual in what we now call simply "knowledge-at-a-distance?"

The instantaneous nature of the "knowledge" is what Einstein saw as a potential violation of his principle of relativity. We argue that it picks out a *special frame* in which two events are "simultaneous."

Relativity denies simultaneity between separated events.

In 1927 at the Solvay conference the events were the detected particle on the screen and that mysterious second place on the screen.[2] In the 1935 EPR paper they were the "influence" of the first particle measurement on the second particle.

Between these two points is a space where Einstein thinks something is happening that violates his relativity principle. In the diagram above it's the line between Alice's observation at t_0 and the point t_0 on the line to Bob where the conserved momentum would locate the entangled particle on its way to Bob.

Events at those two points are "simultaneous" in the frame where the center of the experiment is at rest. There are very fast-moving frames coming from the right, where Bob's measurement at t_1 appears to happen *before* Alice's measurement at t_0.

Now these are the two points where electron spins (or photon polarizations) are measured in the tests of Bell's inequality (chapter 32), where Alice 's measurements "influence" Bob's.

1 See page 207.
2 See page 175

Einstein knew nothing about our puzzles in the "age of entanglement," yet his "spooky actions" are our concerns today!

His colleagues thought Einstein was too old to contribute anything new to quantum mechanics, but his contributions still zero in with a laser focus on today's most profound mysteries. How can his extraordinary mind have been so prophetic?

No Hidden Variables, but Hidden Constants!

We shall see in the next several chapters that many physicists hoped to confirm Einstein's criticisms of quantum mechanics by questioning the "foundations of quantum mechanics." They would offer either new "interpretations" of quantum mechanics, or new "formulations" that add or subtract elements to the theory.

In particular, they followed Einstein's argument that quantum mechanics is "incomplete," and might be completed by the discovery of additional variables.

There may be no "hidden variables," local or nonlocal. But there are "hidden constants." Hidden in plain sight, they are the "constants of the motion," *conserved* quantities like energy, momentum, angular momentum, and spin, both electron and photon. Created indeterministically when the particles are initially *entangled*, they then move locally with the now *apparently* separating particles.

In our extension of Einstein's "objective reality," we assume the particles have continuous paths from the start of the experiment to the final measurement(s), although the limits of quantum measurement never allow us to "know" those paths or any particular properties like the direction of spin components.

Conservation of momentum requires that positions where particles finally appear are equidistant from the origin, in order to conserve linear momentum. And every other conserved quantity also appears perfectly correlated at all *symmetric* positions. It is the fundamental principle of conservation that governs the correlated outcome, not some hypothetical, faster than light, communication of information between the particles at the time of measurement.

And in any case what would a particle as simple as an electron or a photon do with "information" from an identical particle? Indeed. how would the supposed "first" particle "communicate?"

Information is neither matter nor energy, though it needs matter to be embodied in an "information structure," and it needs energy to communicate information to other such structures.

Objective reality tells us that the two particles are (locally) carrying with them all the information that is needed for measurements to show perfect correlations. This is a major problem only because the Copenhagen Interpretation claims that the particles have no properties before their measurement, that each particle is in a superposition of states, so something is needed to bring their properties into agreement at the measurement.

Einstein's "objective reality" asks the simple question whatever could have caused the two particles to disagree? That is impossible without some physical interaction to change one or both of the particle properties. Such an interaction is of course the measurement by Alice (or Bob) that disentangles the particles.

Alice's "Free Choice" of Spin Direction

Following Einstein's false asymmetry that measurements of spacelike separated particles can be made "first" by one observer, it is widely but mistakenly said that Alice's outcome must be "influencing" Bob's.

What Alice does when she interacts with the two-particle wave function Ψ_{12} is to create new *information* that was not present when the particles were initially entangled. It cannot therefore be carried along locally with our "hidden constants" of the motion.

But the new information is created locally by Alice. The nonlocal two-particle wave function makes it available to both particles globally instantaneously, wherever they are.

The classic case of entangled electrons or photons is that they start in a state with total spin (or polarization) equal to zero (the so-called singlet state).

The singlet state is perfectly symmetric in all directions.

When Alice measures a polarization or spin direction, her measurement forces the two-particle system to acquire that overall preferred direction. This is what Wolfgang Pauli called a "measurement of the second kind. Paul Dirac said the system is "projected" into this state. Henry Margenau called it a "state preparation."

Quantum mechanically, the two-particle wave function is in a superposition of states in all directions and Alice's measurement projects it into Alice's freely chosen spin direction.

The two spins before her measurement were opposing one another but had no such preferred direction. Now they have opposite spins and in the direction chosen by Alice. This new information about polarization direction can not have been carried along locally with the hidden constants that conserve all physical properties, because that information did not exist until her measurement. .

Just because we cannot continuously measure positions, paths, and particle properties does not mean that they don't exist. And claiming they are not determined just before measurement asks the question of what forces exist to change them at the last moment?

The new preferred direction for the spins did not exist. They were the result of Alice's "free choice." But the Copenhagen Interpretation is simply wrong to extend the *non-existence* of Alice's new properties to other properties that travel "locally" with the particles

Our "hidden constants" traveling locally with the particles only require that the spins are always perfectly opposite. If Alice's measurement shows a spin component of +1/2 in her chosen z-direction, Bob will necessarily measure -1/2 in the z-direction.

Any other value would violate the conservation laws and break the symmetry.

Note that whether Alice measures +1/2 or -1/2 is random, the result of what Dirac calls "Nature's choice."

If Bob now "freely chooses" in any other angular direction, his correlations will be reduced by the cosine squared of the angular difference between him and Alice. This is the same physics that reduces the light coming through polarizers at different angles as we saw in chapter 19.

We shall see in chapter 32 that John Bell strangely argued that "hidden variables" of the type imagined by Einstein or Bohm would produce correlations with a straight-line angular dependence, and not the familiar sinusoidal relationship .

Decades of Bell inequality tests claim to have shown that hidden variables must be nonlocal. "Hidden constants" like linear momentum and opposing spins are local! They are conserved properties that move along in the entangled particles at or below light speed.

The two-particle wave function is itself a global function encompassing the two particles (and beyond in the case of electrons).

When that two-particle wave function instantly acquires a preferred direction for its opposing spins it does so globally, giving the illusion of an effect or an "action" travelling from Alice to Bob.

But this is precisely the same "nonlocality" seen by Einstein in 1905 and reported by him first in 1927 at the fifth Solvay conference.

It is the mysterious and powerful global property of the wave function that Einstein called "ghostly" and a "guiding field." There is no "spooky action-at-a-distance" in the sense of one particle acting on the other, "influencing" it in some way.

It is the same "guiding" power of the wave function which in the two slit experiment statistically controls the locations of electrons or photons to show interference fringes, including null points where particles never appear.

This power of the wave function explains the mystery of entanglement, why Bob finds perfect correlations with Alice when she measures simultaneously or a moment before him so there is no time for knowledge of her freely chosen angle to travel to Bob.

There are two important moments to be understood, initial entangled formation and later disentangling measurement.

1) At formation, standard quantum mechanics usually describes the entangled two-particle wave function as in a superposition of up-down and down-up states,

$\Psi_{12} = (1/\sqrt{2})\,(|+ - > - |- + >)$.

But Paul Dirac tells us an individual system is in just one of these states from the moment of formation.[3]

The singlet state, say $|+ - >$, is visualized as having no determinate spin direction as the particles travel apart. This spin state is isotropic, spherically symmetric.

We should note that the two spins are not in ordinary coordinate space. Erwin Schrödinger knew his wave function for two or more particles is in a multidimensional "configuration space."

The electron spins may be in still another dimension so the spins ae not separated at all ordinary space-time!

3 See page 151.

2) The two-particle state collapses on Alice's measurement into a product of single-particle states, | + > |- >.

When Alice measures her particle with her "free choice" of a definite spin direction, e.g., z+, it is the requirement to conserve total spin, not any communication, that projects Bob's particle, before his measurement, into z-. The particles are disentangled.

Just before Bob's measurement, his state has been *prepared* so that if he measures in Alice's direction, he will measure z- (say spin down) to her z+ (say spin up).

The two particles have been conserving zero total spin from the time of their singlet state preparation at the start of the experiment and, if undisturbed, they will be found in the same singlet state when they are measured. They have perfectly correlated opposing spins when(ever) they get jointly measured at the same angle.

The particular direction of spin is created by Alice.

One of Einstein's great principles was simplicity.[4] It is also known as the law of parsimony and Occam's Razor. The idea is that the simplest theory that fits all the known facts is the best theory. Einstein may have liked the idea that the most true theories would be beautiful in some sense, perhaps as the result of their symmetry.

Consider then the simplicity and parsimony of the idea that entangled particles, once "cross-linked" and sharing an antisymmetric two-particle wave function, are carrying with them at all times all the information needed for them to *appear to be* coordinating their actions - without communicating!

The information is "hidden" in the "constants of the motion." And where hidden variables are nonlocal, all hidden constants are local.

It is now fifty years since the first laboratory experiments were done to find whether quantum mechanics might be faulty, and hidden variables might be needed to explain entanglement.

There has been no evidence that anything is wrong with quantum mechanics. Isn't it time that we go back to Einstein's first principles and see whether the "objective reality" of continuous particle motions carrying with them all their conserved properties can give us a very simple, easy to explain, understanding of entanglement?

4 See chapter 35.

We can have entanglement without "action-at-a-distance."

Information hidden in the constants of the motion is "locally real" at all times as the particles travel apart with no definite spin directions for either particle, but total spin always zero.

Can Conservation Laws Do It All?

But can conservation laws and symmetry explain the perfect correlation of every particle property to prove there is no instantaneous "action-at-a-distance" needed for entanglement?

All physicists know conservation works for linear momentum. Einstein used it in his 1933 letter to Leon Rosenfeld. But what about the properties tested in all modern experiments on entanglement, electron spin and photon polarization?

Can we show how these properties also are actually conserved as they are carried along with the particles, so there is no need for instantaneous communication between two widely separated entangled particles at the moment of their measurement, eliminating the conflict between quantum mechanics and special relativity?

The case of the photon is relatively straightforward, as we saw in Dirac's analysis (chapter 19). He said that an individual photon is not in a linear combination or superposition of states, as we assume when making predictions for a number of experiments.

We can simplify the two-particle state to either $| + - >$ or $| - + >$.

And since the two-particle, spin-zero, state has no preferred spin or polarization direction, we can say that they are in a superposition of possible spin or polarization components, and that the spin of one is in some average sense always opposite to that of the other.

"Objectively real" entanglement is in no sense a measurement of one particle "acting on" and causing a change in another distant particle. When Ψ_{12} decoheres, particles appear simultaneously in our *special* frame of reference. No properties are changing.

Einstein's "objective reality" requires that entangled particle properties are conserved from their initial state preparation to their ultimate measurements, giving the *appearance* of instantaneous communications, of Einstein's "spooky action-at-a-distance."

Pauli's Kinds of Measurement Again

When we describe the measurements of entangled particles that "collapse" the two-particle wave function, and which make the particles in a spacelike separation *appear* to interact instantaneously, infinitely greater than lightspeed, we must consider what kind of measurements are being made.

As we saw in chapter 19, Wolfgang Pauli distinguished two kinds of measurements. The first is when we measure a system in a known state ψ. (It has been prepared in that state by a prior measurement.) If we again use a measurement apparatus with eigenvalues whose states include the known state, the result is that we again find the system in the known state ψ. No new information is created, since we knew what the state of the system was before the measurement. This Pauli called a *measurement of the first kind.*

Dirac noted that quantum mechanics is not always probabilistic. Measurements of the first kind are *certain*, like preparing a state and then measuring to see that it is still in that state. Today this is called a non-destructive measurement.

In Pauli's second case, the eigenstates of the system plus apparatus do not include the state ψ of the prepared system. Dirac's transformation theory says one should use a basis set of eigenstates appropriate to the new measurement apparatus, say the set φ_n.

In this case, the original wave function ψ can be expanded as a linear superposition of states φ_n with coefficients c_n,

$\psi = \Sigma_n c_n \varphi_n$,

where $c_n{}^2 = | < \psi | \varphi_n > |^2$ is the probability that the measurement will find the system in state φ_n.

Pauli calls this a *measurement of the second kind*. It corresponds to John von Neumann's Process 1, interpreted as a "collapse" or "reduction" of the wave function. Von Neumann said that new information is irreversibly recorded in the measuring apparatus.

In this measurement, all the unrealized possibilities are eliminated, and the one possibility that is actualized produces new information. We do not know which of the possible states becomes actual. That is a matter of ontological chance. If we did know in advance, there would be no new information.

Measurements of electron spin are done with Stern-Gerlach magnets. A stream of electrons with random spin directions passing through a magnet oriented in the z-direction separates into electrons deflected upward (z+) and those deflected downward (z-).

This is a measurement of the second kind, a state preparation. If we pass all those with z+ through a second magnet in the z-direction, they all are deflected upward again. This is a non-destructive measurement of the first kind. Information is preserved.

If those electrons in a known z+ state are passed through a magnet oriented in the x-direction, they are observed in a random distribution of x+ and x-. The z+ state information is lost.

At the initial entangled state preparation, neither electron has information about its spin components. Since there is no information, we can call this a measurement of the zeroth kind.

This describes the preparation of the entangled pair. We know nothing of the spin components of the electrons (or polarization of photons). But we do know that the spin of the left-going particle will be opposite to that of the right particle when they are measured.

Assume that Alice measures "first", which she does if she is closer to the center than Bob. This is a measurement of the second kind, because a preferred spin direction of the electron did not exist.

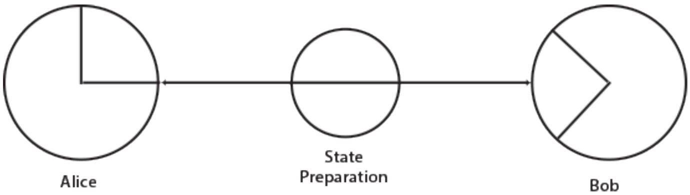
Alice makes a "free choice," as Heisenberg described it. The spin component value comes into existence. It did not necessarily have that value before her measurement. No matter which angle of orientation Alice measures, she will find spin randomly +1/2 or -1/2. Dirac called this "Nature's choice."

Between "Nature's choice" (quantum chance discovered by Einstein in 1916) and "free choice" (Einstein's "free creations of the human mind"), we untie the Gordian Knot of quantum mechanics! Neither we nor the universe are pre-determined.

If Bob measures the same angle as Alice (perhaps by prior agreement) and compares measurements later, he will find his data is perfectly correlated with Alice. Bob's measurement in the same direction as Alice is therefore a measurement of the first kind.

Alice prepares the state. Bob measures the same state.

If, however, Bob sets his apparatus to measure at a different angle, he finds a weaker correlation with Alice over several measurements.



Bob also has a "free choice" as to what to measure. As he varies his angle away from Alice's, at first only a few measurements disagree, randomly but then disagreements increase, following the cosine dependence of light passing through rotating polarizers. [5]

John Bell made the very unphysical claim that the correlations would fall off linearly, in a straight line, and connected this "inequality" to Einstein's idea of additional ("hidden") variables. [6]

If Bob rotates his apparatus to 90°, spin in the x direction will be completely random. All correlations with Alice are now lost.

These measurements of the second kind project Bob's electron spin in a new direction . It prepares a new state. It does nothing to Alice's particle, since her measurement separated the electrons.

The reason Alice and Bob measure perfect entanglement when they measure in the same direction is because both spin directions were determined by Alice at the moment the two-particle wave function | + - > collapsed and projected out the two values, +1/2 and -1/2, conserving the total spin as zero.

The total spin was zero before her measurement, but it had no definite spin component direction

This was not "spooky action-at-a-distance" traveling from Alice toward Bob. The collapse of Ψ_{12} is symmetric (or anti-symmetric) in all directions. It is this symmetry, and the conservation law for total electron spin, that completely explains entanglement.

The original state preparation of entangled particles created no new information about specific spin components. With some deep

5 See Dirac's polarizers in chapter 19
6 See chapter 32.

symmetry (photons) or anti-symmetry (electrons), it does not prepare the particles in definite states, as does Alice's measurement.

We could call this a measurement of the zeroth kind.

Alice breaks the original symmetry, creating information about the new spin directions. If Bob measures at the same angle, it is a measurement of the first kind. If he measures at other angles, symmetry/anti-symmetry with Alice is broken and Bob's is a measurement of the second kind.

How Symmetry and Conservation Explain Entanglement

When a pair of electrons or photons is entangled, they are not prepared with spins that have definite components in specific spatial coordinate directions. But they must be such that if one is found to have spin +1/2 in any direction, the other will be -1/2. And these opposite directions will show up when Alice's measurement projects her electron and Bob's into definite directions.

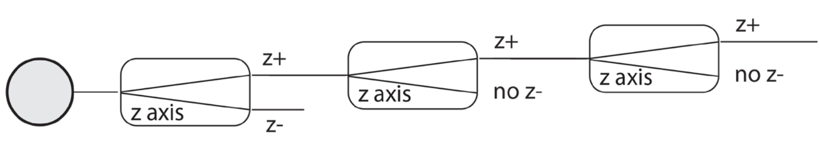
The two electrons could be in a superposition of | + - > and | - + >, as standard quantum mechanics likes to say. They may only acquire specific spin component directions when Alice's measurement projects the two-particle wave function into a definite direction.

Or it could be that Dirac is correct that they are in one or the other of these states from their entanglement. In this case, Einstein is right that they have all properties before they are measured. But they cannot yet have definite z spins. Einstein would understand this as the consequence of a new measurements.

Let's see how to visualize this in terms of Pauli's two kinds of measurements and a state creation that is *not a measurement* which leaves two entangled electrons in perfectly symmetric *directionless* spin states that together preserve total entropy zero.

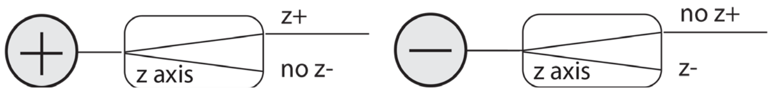
First let's recall how measurements of spin in a Stern-Gerlach apparatus can distinguish electrons that are in a known state from those that are in a symmetric state with no definite direction.

The gray circle represents an unentangled electron with no specific spin direction. When that electron enters the magnet which is oriented in the z direction, it is either directed upward or downward. This a measurement of the second kind.

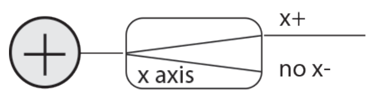


If it prepares a spin-up electron z+ and we pass it through a second magnet (or even a third) with the same z orientation, it does not change from z+. These are non-destructive measurements of the first kind. It never yields z- electrons

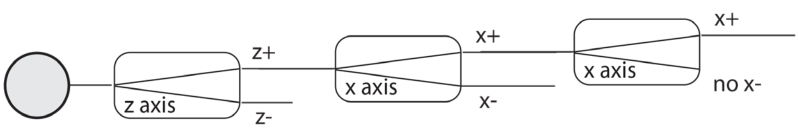
When we know a determined state goes in, the same comes out. Suppose we had a pair of entangled electrons with no determinate spin directions but with one carrying the positive spin and the other the negative. What happens as they pass through the magnets?



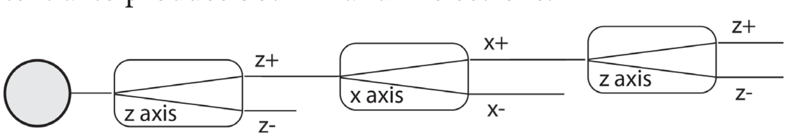
The positive spin electron, which has no determinate direction component, comes through the magnet projected into z+. Such a spatial directionless positive spin electron sent through an x-axis magnet produces only x+ electrons.



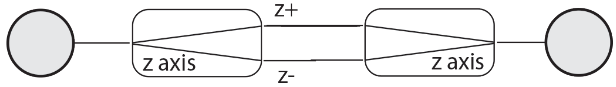
We must now recall what happens when we pass an electron with known spin z+ through a magnet oriented in the x direction.



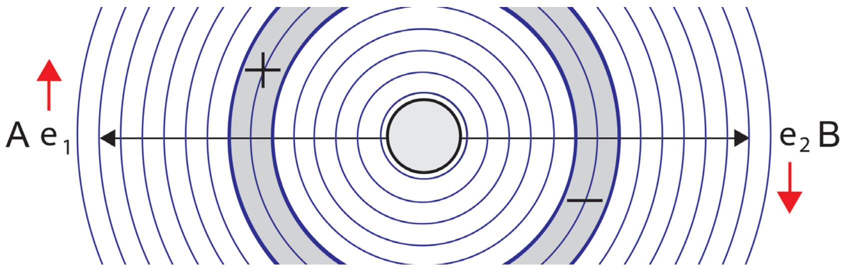
Both x directions are possible, and when a known x+ is produced, subsequent measurements of the first kind keep it the same x+. Now before we show how our entangled electron behaviors work to explain entanglement, we should show the loss of z+ spin when passed through a magnet oriented in the x direction, and the subsequent recovery of both z+ and z- components. An x+ electron contains the potential to produce both z+ and z- electrons.



Finally, so we show all the amazing properties of electron spin, and add to understanding the idea of an electron with a spin value, but with no preferred spin direction, we can use a Stern-Gerlach magnet to generate both z+ and z- and, providing we do not make a measurement, send them though in the opposite z direction to recreate the original.



So let's see how our directionless spin states travel from their entanglement and then get projected into opposite spin directions by Alice and Bob .



At the start the two electrons are in the same small volume of phase space with their spins opposite, satisfying the Pauli exclusion principle, like the two electrons in the ground state of Helium.

A few moments later they travel apart in a |+ - > state, with one electron having spin +1/2 and the other -1/2. But neither has a definite spatial spin component, in a given direction such as z+.

The *directionless* spin state is symmetric and isotropic, the same in all directions. It is rotationally invariant. The spin values of + and - are conserved quantities we can call *local* "hidden constants," traveling with the particles from their entanglement in the center.

Because they are entangled, the + spin in one electron is always perfectly opposite that of the - electron, though the spatial direction of the spins is entirely unknown.

These conserved spins provide the necessary information that hypothetical "hidden variables" could provide to the electrons at their moment of measurement. But no faster-than-light exchange of that information is involved, no "signaling" between the particles in a distant spacelike separation. Correlation information is carried along with the electrons at their speed. Their spins are always perfectly correlated, not suddenly correlated at the moment of measurement, as the Copenhagen Interpretation claims.

In her measurement, Alice *creates* new directional information that did not travel with the "hidden constants" of the motion. It was unknown beforehand. When Alice measures in the z direction, she "prepares" the state z+. But Einstein's "objective reality" view is correct that the system has most of its properties *before* her measurement.

In his original EPR, it was linear momentum that was conserved from the initial interaction. Conservation laws allowed him to know something about particle 2 simultaneous with his measurement of particle 1. This is not "action." This is just "knowledge-at-a-distance."

But there is one property the two particles could not have before Alice's measurement. It is something Einstein never thought about. That is the spatial direction of the polarization or electron spin imposed by Alice's "free choice" of which angle to measure.

If Bob also measures at Alice's angle, Bob's is a measurement of the first kind. The state that he measures was prepared by Alice. These are two perfectly correlated events that are *simultaneous* (in a "special frame") despite being in a spacelike separation.

When Einstein first saw this kind of nonlocal phenomenon in 1905 and described it in 1927, he thought it violated his special theory of relativity, and his idea of the *impossibility of simultaneity.*

Nevertheless, this is one more amazing insight into nature that Einstein was the first person to see, even if it bothered him.

These simultaneous spatially separated events are a consequence of the two-particle wave function Ψ_{12} collapsing into the product of two single-particle wave functions Ψ_1 and Ψ_2

The Ψ_{12} wave function has decohered, the particles are disentangled, they acquire their opposite spin component directions, + spin goes to z+, - spin to z-.

In all entanglement experiments, these simultaneous values of opposing spins or polarizations that appear now have definite spatial directions, which is *new information*. The z+ and z- values are "nonlocal." The +1/2 and -1/2 spins came with the particles, as Einstein hoped to show. They are "local," like the particle momenta.

Then again, if the spins live in their own space, they may not be separated by a metric element in four-dimensional space-time!