Quantum Spooks

Now that we've seen a bunch of interesting quantum effects, for our last long walk let's venture into a particularly creepy corner of the quantum wood. Today we're going to see entanglement and measurement order, which create some of the most counter-intuitive effects in quantum mechanics. These are so counter-intuitive that this is probably a good time to re-emphasize that nothing in this series is speculative—everything we've seen is backed by hundreds of observations. Sometimes the world is much stranger than we expect it to be.

I've always considered the world of spies and espionage to be strange and spooky, so maybe it is fitting that one of the applications of what we are talking about today is unbreakable quantum cryptography. But we'll have to explain a few things before we get to that.

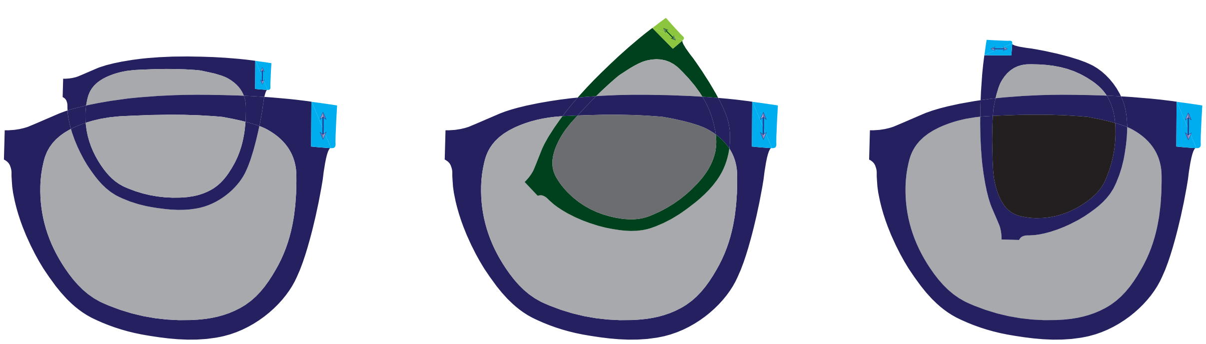
Playing in the sunlight

After a long walk through an increasingly dark and gloomy forest, gnarled trees dripping with vines, we unexpectedly emerge into a meadow sparkling in bright sunlight. Blinking in the light we pull out our polarized sunglasses.

[Sidebar: If you've never played with polarized sunglasses, it is great fun to look at different objects while tilting your head in various directions (or holding the glasses in front of you and rotating them if you want to look slightly less like a doofus—whatever you do, please don't look at the Sun.) Some things will look the same regardless of how you rotate the glasses: concrete, trees, and houses all reflect unpolarized light. Others will dramatically change brightness as you rotate the glasses: reflections off of water and car windows, the blue sky (tangential to the direction to the Sun), and most LCD computer monitors. That's because these objects reflect or emit polarized light.]

The lenses in polarized sunglasses are polarized in the vertical direction, meaning when worn normally they will allow light polarized vertically to pass through while completely blocking horizontally polarized light. This is advantageous because light glinting off of water is mostly horizontally polarized, so a lens that only allows vertically polarized light through will greatly reduce the reflected glare.

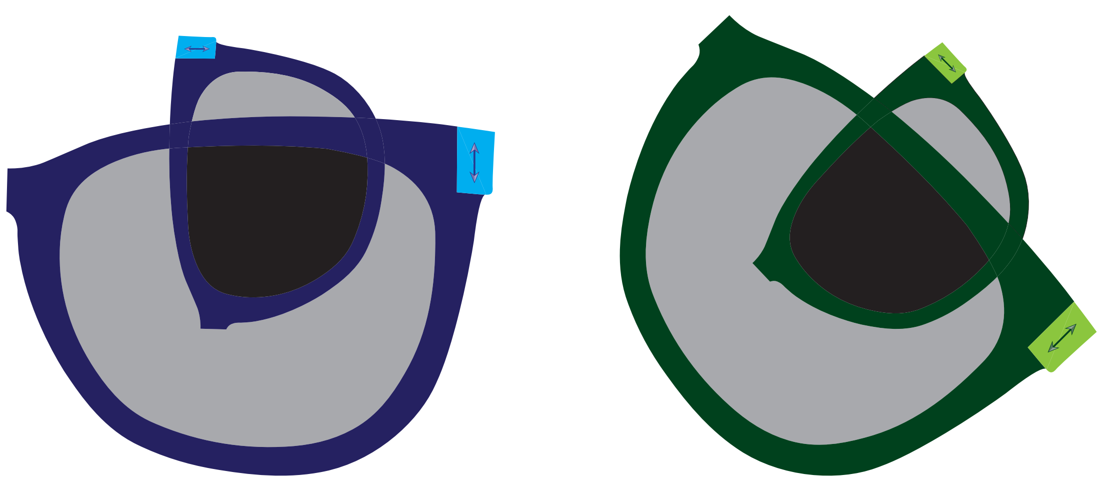
Being a little suspicious of the beautiful sunshine in our mysterious glade, we start looking through multiple pairs of sunglasses. Squinting through two or three pairs of sunglasses at the same time does make you look ridiculous, but such are the sacrifices we make for science. We'll diagram the results you would see, but if you can scrounge together three pairs of polarized sunglasses you can perform all of the experiments in this article at home (you get bonus points for doing this while standing at the sunglasses stand at a local convenience store).



[What you see when looking through two polarized sunglasses. Each polarized lens only lets through light that's polarized in the direction of the arrow on the temple. Since the background light is unpolarized, all of the lenses will let through half of the background light (the medium grey tint). But when light has to pass through both glasses, the relative orientation of the glasses matters. On the left, both lenses are letting through vertically polarized light, so all of the light that makes it through the first lens also goes through the second lens. In contrast, on the right, the glasses in the back are rotated to only let through horizontally polarized light, which is entirely blocked by the front glasses. If you hold the glasses at a 45° angle with respect to one another, half of the light going through the first pair of glasses will make it through the second pair (1/2 x 1/2 = 1/4 of background light).]

If you hold two pairs of the glasses in front of you and then rotate one of the pairs, you will notice that the amount of light passing through varies *dramatically*. When the glasses are at a 90° angle (e.g. one held normally, and the other pair sideways) almost no light will get through. The combined view through the lenses will look almost completely black, and for really good polarized lenses they will get almost welding-glass dark. Conversely, when held with the same orientation, they let almost the same amount of light through as one pair of glasses alone (with good polarizing lenses held in perfect alignment, this is exactly true).

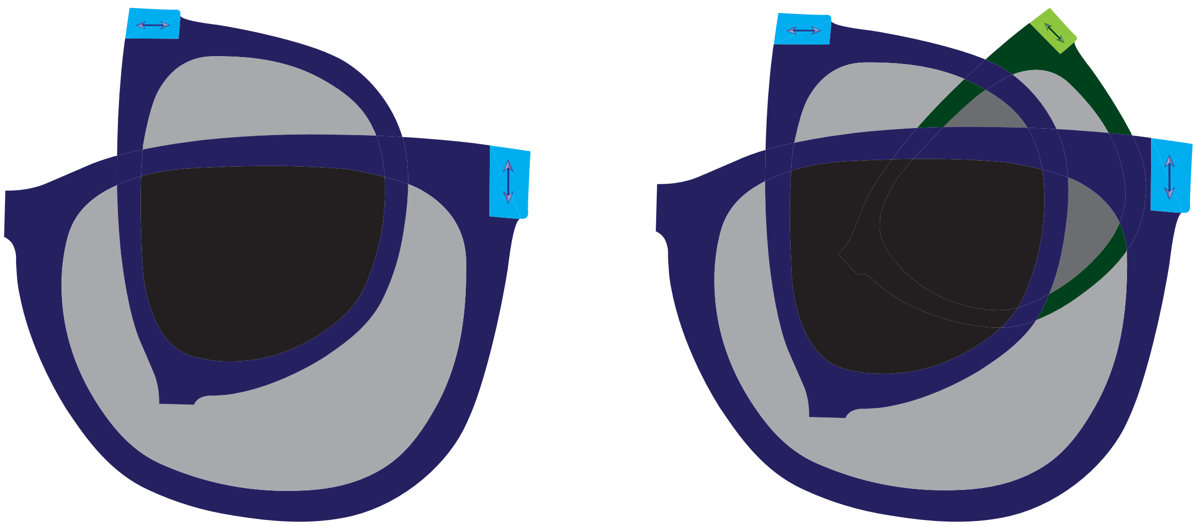
This is fairly straightforward to understand. If both glasses are held vertically, the first pair of glasses only lets vertical light through. Since the second pair also lets vertical light through, it has nothing to block—all of the light that made it through the first pair will also make it past the second. Conversely, if we hold the first pair sideways so it passes only horizontal light and hold the second pair normally so it blocks horizontal light, then there is no light that can get through both. Together, they appear very dark. And if you hold the glasses at a 45° angle to each other, it's intermediate; half the light passing through the first pair of glasses gets through the second.



[Figure showing crossed lenses.]

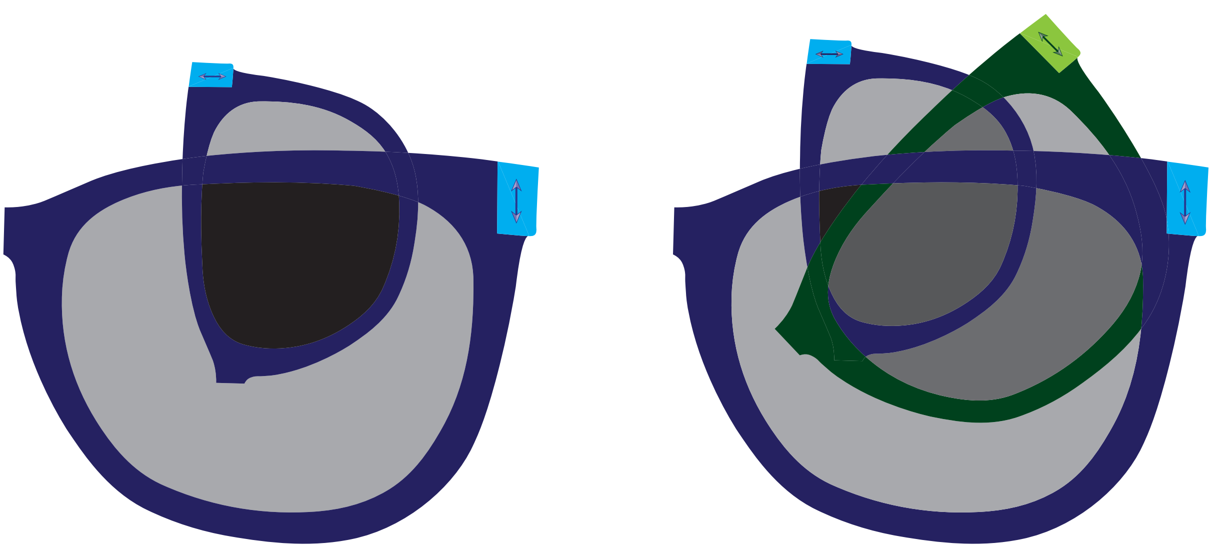
It's only the angle between the lenses that matters. If we pick a relative orientation, such as crossed, and rotate both lenses together, we'll see the opacity stays the same. The green-framed glasses on the right are held at ±45° to the vertical, but since the first pair lets through light polarized 45° left of vertical, all of the light is blocked by the closer pair that passes only light polarized 45° right of vertical.

This all seems to make sense. But then you remember this is quantum mechanics, and the ominous movie music starts to play in the background. Let’s add a third pair of glasses. And to help keep all the orientations straight, we will always use blue frames for the horizontal/vertical orientations and green frames for the ±45° orientations.



[Starting with crossed lenses, and adding a diagonal lens behind them.]

We will start with two crossed glasses, as shown on the left. We will then add a third lens oriented at a 45° *behind* the two we already had. On close examination, this behaves as we’d expect. Anywhere the original glasses block the light is still black. In the little corners where there’s not complete overlap, the light goes through the 45° lens and one of the other lenses and we get the slightly darker tint we saw back in Figure 1. If we look at what’s new, we see that the region where the light must pass through all three lenses is also black.



[Starting with crossed lenses, and adding a diagonal lens between them.]

But we see something remarkable if we reorder the glasses. We again start with crossed glasses, but now slide the 45° lens *between* the crossed lenses. When we do this, light gets through where all three lenses overlap. Where only two lenses overlap we get the expected results—black for crossed and tinted for 45° relative orientation. But even though the front and back lenses are crossed and would normally let no light through, if you interpose another lens with intermediate polarization, suddenly light can pass through.

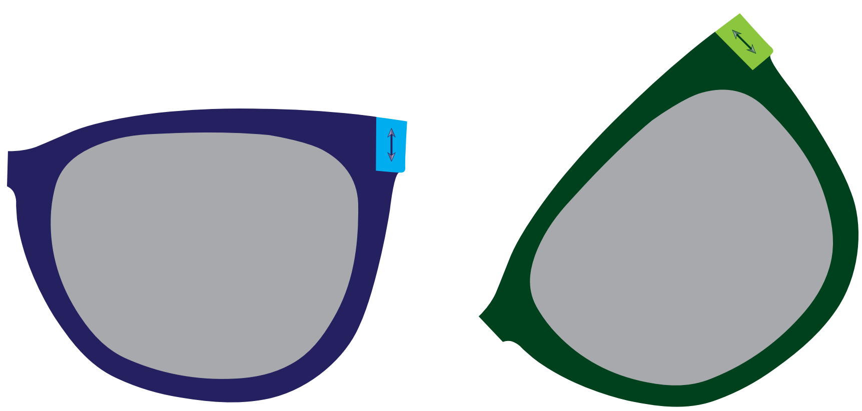
This is weird. The *order* of the glasses matters. If you are following along at home, try flipping the order of the lenses. If crossed lenses are next to each other in the stack, no light gets through. But if you alternate between blue (horizontal/vertical) and green (±45°) frames, some light will get through.

Wearing sunglasses at night

In the bright sunlight we saw that various fractions of the light got through depending on how the polarized sunglasses were oriented—from half the light when the lenses were oriented the same way to none at all when crossed. But what happens if there is only one photon?

Faint stars are my favorite source of single, unpolarized photons, so if we wait in our spooky meadow till nightfall, we can observe how single photons pass through the sunglasses.

If we look at a star with one polarized lens, half of the photons will get through. Whether a photon will go through or be absorbed by the lens is random—and not "kind of random," but perfectly random. It is so perfectly random that the passage of starlight through a polarized lens can be used to create the highest quality random numbers known to humankind—there is actually a market for random numbers generated in this way.



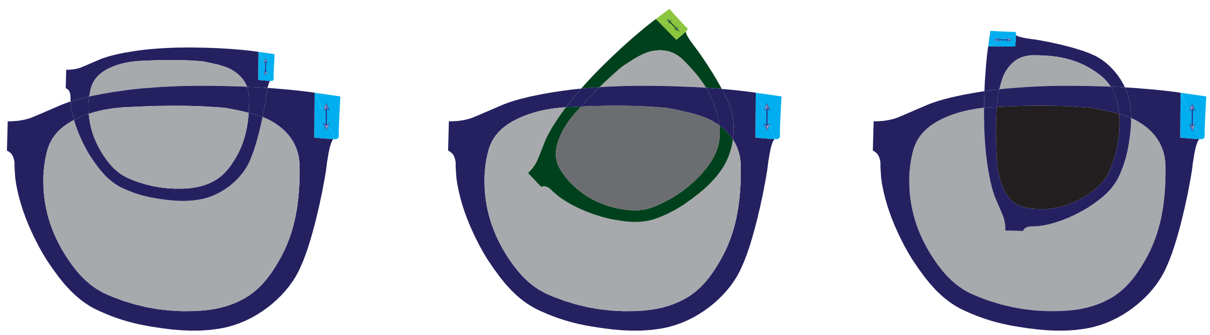
[Regardless of how the glasses are held, exactly half of the unpolarized single photons will pass through the lens. Whether an unpolarized photon passes through the lens is *perfectly* random.]

The question now becomes what happens to photons when passing through two stacked lenses? We'll start with lenses oriented in the same way (below left). When unpolarized starlight hits the first lens, half of the photons are randomly absorbed. But the 50 percent of the photons that were lucky enough to make it through the first lens *all* make it through the second.

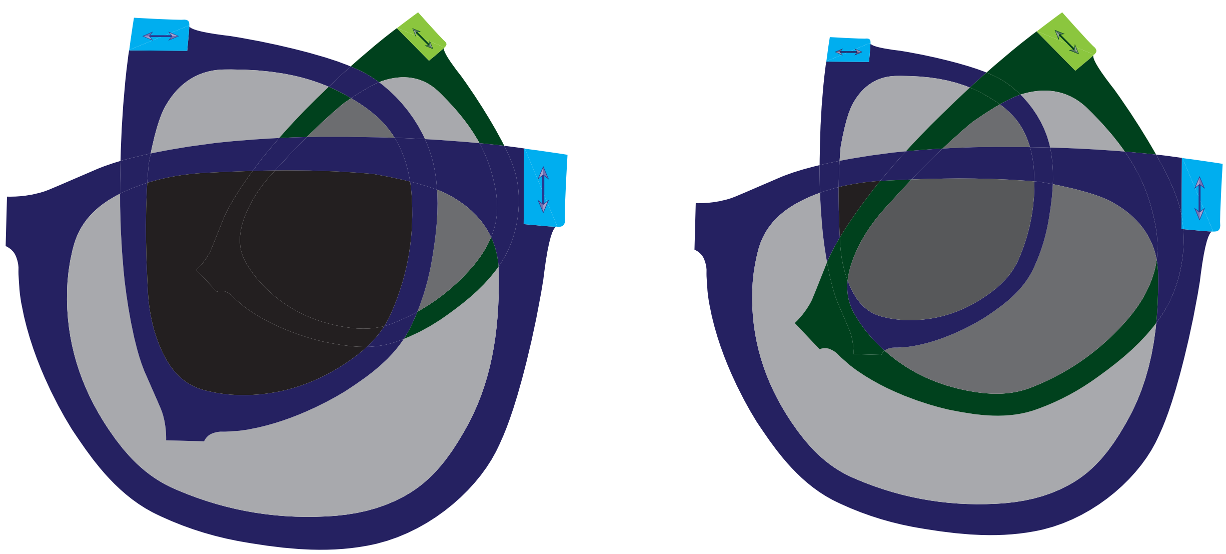
Or said another way, 100 percent of the photons that made it through the first lens make it through the second.

If we turn the lenses 45° relative to one another (middle), we know fewer photons will make it through. But what is the pattern? It turns out that of the 50 percent of photons that pass the first lens, half will also make it through the second, giving us a total of 25 percent making it through. And this 50 percent chance of getting through the second lens is again perfectly random. It is like the photons rolled the dice again.

Lastly, if we have two crossed lenses (right), there is no chance of a photon that passed the first lens gets through the second.



The more we play around with things, the stranger this becomes. If we use two blue framed glasses or two green framed glasses, whether a photon makes it through the second lens is deterministic (100 percent or 0 percent). But if we use one lens from the blue glasses and one lens from the green glasses, whether the photon makes it through the second lens is random. It turns out this works in any combination. Any two glasses of the same frame color is deterministic, and two glasses of different frame color is random. And it is this difference between deterministic and random that enables quantum cryptography.



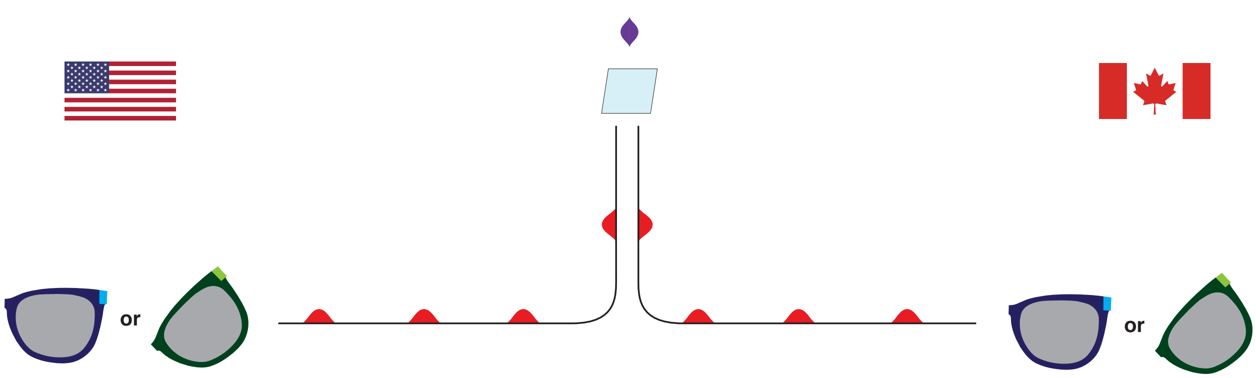
This also helps us understand the three lens sets. When the blue framed lenses are next to each other, as in the left stack, whether a photon makes it through the next lens is deterministic (zero in this case). But in the right stack we keep alternating the color of the glasses frames. So there is a 50 percent chance of the light after the first blue framed lens making it through the green, and another 50 percent chance of the light from the green framed lens making it through the frontmost blue framed lens. Because at every stage the chance of making it through was random, some of the light gets lucky and makes it through (1/2 x 1/2 x 1/2 = 12.5 percent).

We were able to take the four orientations of sunglasses we considered and sort them into two sets—blue framed vertical and horizontal, and green framed ±45°. Within frames of a set, the probability of a photon passing the second lens is deterministic (100% or zero); but when using frames of different sets (green with blue) the probability of the photon passing the second lens was perfectly random. This means we have the ability to sort our measuring devices—polarized sunglasses in this case—into sets that are internally deterministic, but mutually random. This is a very deep feature of quantum mechanics, a property of our world we can see by looking at the stars with sunglasses on.

Why spies wear shades?

Crystals, like those found in rock shops, have remarkable abilities to bend and reflect light. And some special crystals can take one photon of light and split it into two photons. These daughter photons will head off in different directions, each with about half the energy of their parent photon. If the photon splitting is done with care, the daughter photons look like twins—they will always have the same polarization.

Any good study of twins inevitably involves separating them. So we'll put our twin photons into separate fiber optic cables and send them to different cities, say Detroit (USA) and Windsor (Canada), where we can look at them using either blue or green framed polarized sunglasses. We'll make a series of twinned photons; to make the bookkeeping slightly easier we'll limit ourselves to the two lenses shown and always look at the twin in Detroit first.



[Making photon twins and sending one twin to Detroit (USA) and the other to Windsor (Canada).]

If we use the blue framed sunglasses in Detroit, each incoming photon has a random 50-50 chance of being absorbed and being transmitted. If we write down whether each photon was absorbed or transmitted with 0's (absorbed) and 1's (transmitted), we get a long perfectly random sequence. And if our friend in Windsor looks at their stream of photons with the same blue framed lens, they will also see a long random sequence of photons being absorbed and transmitted. So far so good.

		➔														
	0	1	0	0	1	1	0	0	0	0	1	0	1	1	0	0
		➔														
	0	1	0	0	1	1	0	0	0	0	1	0	1	1	0	0

[The record for both Detroit (USA) and Windsor (Canada) of whether the photon twins were absorbed (0) or transmitted (1) when they both use blue framed lenses.]

But if we pick up the phone and compare notes, we discover that we both saw the *same* random sequence. Whenever a photon was absorbed in Detroit, its twin was also absorbed in Windsor. Whenever a photon was transmitted in Detroit, its twin was transmitted in Windsor. This is a natural consequence of the photons being twins. If the twin in Detroit passes through the lens, it has a vertical polarization, and its twin must also have a vertical polarization. So the twin will also pass through the lens in Windsor if it's in the same orientation. When we both use the blue framed lenses, there is a deterministic relationship between the photon twins.

But what if we use the blue framed lens in Detroit and our friend uses the green framed lens in Windsor? We repeat the experiment with a bunch of newly generated twinned photons, and as before, both see a random 50-50 sequence of photons being transmitted and absorbed. But when we pick up the phone to compare results, this time there is no relationship between what we see. If the photon in Detroit was absorbed by the blue framed lens, there is a random, 50-50 chance of its twin being absorbed or transmitted by the green framed lens in Windsor. Just like when we looked at starlight through two stacked lenses, if we both use the same kind of lens there is a *deterministic* relationship and when we use lenses from different sets (blue frame and green frame) the results are *random*.

		➔														
	0	0	0	1	0	0	1	0	1	1	0	1	0	0	1	1
		➔														
	1	0	0	1	1	0	0	1	0	1	1	1	0	0	0	1

[The record for both Detroit (USA) and Windsor (Canada) of whether the photon twins were absorbed (0) or transmitted (1) when Detroit uses a blue framed lens and Windsor a green framed lens.]

Now this is odd. The photon in Windsor seems to 'know' what happed to its twin in Detroit. If the photon in Detroit encountered a blue framed lens, and the photon in Windsor sees a blue framed lens, it seems to know what to do (deterministic). Similarly if they both see green framed lenses they know what to do. But if the photon in Windsor sees a different kind of lens, it is free to do whatever it wants (random transmission or absorption). How does each photon in Windsor know what its twin in Detroit saw?

We can test this by trying all of the different combinations of lenses in Detroit and Windsor. Even if we randomly change which lenses are used for every photon that arrives we always see the same pattern: the results are deterministic when twinned photons see the same lens and random if when they do not. The photon in Windsor knows what happened to its twin.

We can even wait until the last moment to decide which lenses to use. In Detroit, we can wait until the photon has almost reach us before we decide whether to use the blue frame or green frame lens. Even if there is not enough time for light to run from Detroit to Windsor before the second photon encounters its lens, it already knows what happened to its twin. As far as we can tell, the photon in Windsor knows what happened in Detroit *instantly*.

This is such a weird answer, and no it doesn't make intuitive sense. Physicists have tested this in every way we know how: randomly choosing lenses at both Windsor and Detroit, making sure the decisions are truly unpredictable, greatly increasing separation between the laboratories. No matter how fast or mischievous we get, the second photon seems to knows instantly what happened to its twin. Current limits are better than 1,000 times the speed of light.

It is at this point that a small sinister man steps into the clearing and flashes an identification badge. He's from your national espionage agency, and he quietly walks up to us and says, "I think it is time we had a little talk." He turns to leads us out of the quantum woods, as you notice the iridescent frames on the sunglasses he is wearing.

Terms of Entanglement

The instantaneous relationship between twinned photons is so unexpected. Not only have we tested it in thousands of ways, it turns out it is an important ***feature*** of the way our Universe works.

Having a deterministic relationship between two (or more) particles is called *entanglement*. As with any quantum effect, it applies to all types of particles. It is even possible to create deterministic relationships between different kinds of particles—one of the promising quantum computer prototypes entangles photons with Strontium ions (~174 constituent protons, neutrons, and electrons).

In this article, we have actually explored three closely related effects. With the sunglasses we saw we could categorize measurements into sets (blue frames vs. green frames), where the observations within a set are deterministic but observations between sets are random. This leads to measurement order being important. When looking through three sunglasses, we saw light get through with one ordering and not through another. The non-commuting algebra involved here is one of the things that makes the math of quantum mechanics so hard.

We also saw with the twinned photons that it's possible to create a deterministic relationship between two particles. This has the bizarre effect of ensuring that the related particles instantly know what happens to its sibling.

Together, these are the most counter-intuitive aspects of quantum mechanics; it doesn't feel like this is how our world should work. But it does. Not only are these effects real, they are necessary. From the extrovert & introvert bunching of particles we saw back in article three to the precise colors emitted by atoms in the Sun, these three related effects underpin how the world works—the Universe would be a different place without them. And we can put them to practical use; quantum computers are only possible because of entanglement. A strange feature of how particle siblings interact is the basis for an entirely new technology.

Back at the Unmarked Government Building (aka Visitor's Center)

After a long and odd interview, the spy with the iridescent sunglass frames hands us a business card and tells us to stay in touch.

When we measured the twinned photons with the same polarizing lenses, we saw identical copies of a perfectly random sequence. To a spy this is immediately interesting.

Perfect encryption is possible when you have two—and only two—copies of a long random number sequence. You can combine your secret message (in binary) with a random sequence of the same length (the key), and the resulting encrypted message cannot, even in principle, be cracked. Only the person with the other copy of the random number can unlock the encryption and read your Very Important Message™. This was used back in World War II in the form of one time pads [link].

The trick is making sure no one makes a copy of the random key. If there are three copies, and the Very Bad Man (VBM) has one of them, he can decode your message. Much of traditional spycraft boils down to making sure no one can intercept and copy one of the two random keys.

It only takes two small modifications of our earlier experiment with twinned photons to ensure that the key was not intercepted and copied in secret.

In the first modification, both Detroit and Windsor randomly choose blue or green framed lenses for each pair of twinned photons. It doesn't matter which lens they choose each time, just that about half the time they choose a blue frame and half the time a green.

They keep this up for quite a while, getting thousands of random 1's and 0's. They then pick up the phone, but instead of telling each other whether they saw each twinned photon transmit or absorb (1's and 0's), they only say which color frame they chose. Half the time they will have used different lenses, so they throw all those reading away. But when they happened to both have chosen the same frame color, they will have gotten the same readings.

For this subset of twinned photons, the results are deterministic and they will have both seen the same 0's and 1's. Because they only told each other which twins to use, not what the measurements were, the VBM would not know the key necessary to decode the message even if he listened to the phone call.

																
	1	0	0	0	0	1	1	1	0	1	0	0	0	1	0	1
																
	0	1	0	0	0	1	1	1	1	1	0	1	0	1	0	0

[Both Detroit (USA) and Windsor (Canada) randomly choose glasses and record whether the photon was absorbed (0) or transmitted (1). They then talk on the phone and say *only* what color of frame they chose for each pair. For the subset of twins where they both happened to choose the same frame (blue background), they know that they will get the same readings. So they keep these as their shared random key and discard the others.]

But what if the VBM cut the fiber and intercepted one of the photon twins? This is like catching the courier carrying the encryption keys—can't he then copy the key? It turns out there is an easy defense for this that leverages the quantum nature of entanglement. The VBM *can* cut the fiber to Detroit, make a measurement, and send an imposter photon on to Detroit. But which lens should he use? The VBM does not know if Detroit is going to use a blue or green framed lens (Detroit may not even have decided yet).

The VBM has to guess which lens Detroit will use, and about half the time the VBM will guess wrong. When the VBM picks a blue frame, but both Detroit and Windsor pick green frames, the deterministic relationship between what Detroit and Windsor see is broken. The relationship the scheme relied on was between the true twins, not the photon Windsor sees and the imposter send to Detroit.

So to protect against interception, all Detroit and Windsor have to do is compare a small subset of their readings when they picked the same lens. If no one was listening, 100 percent of the time they will have the same reading. But if the VBM is listening, then there is no correlation when the VBM guessed wrong and injected an imposter. Working through the math, only 75 percent of the readings will agree. Windsor and Detroit will immediately know that someone was listening and the rest of the key should be discarded.

This is the holy grail of encryption: a shared random key where you can guarantee that no one intercepted the messenger and made a copy. It is a little disturbing how excited three letter agencies are about this capability. And it's not a potential interest, as quantum cryptography is already here. While there are still limitations on the range and speed, quantum cryptographic links are in production and use.

One more hike

Next week we will wrap up our series. Instead of focusing on some strange and beautiful feature of quantum mechanics, we'll instead survey the wide range of the quantum technologies that will soon permeate our lives. In the process, we'll try to tackle the larger question of what does it mean to be technologically literate in a world infused with quantum machines.

FAQ

Doesn't instantaneous correlation mean we can communicate faster than the speed of light? Sadly we have not invented ansibles [https://en.wikipedia.org/wiki/Ansible]. You will note that whatever lenses the friends in Windsor and Detroit use, they always see a random sequence (50-50 chance each photon will be absorbed or transmitted). It is only when they pick up the phone and talk, which happens at normal light speed, that they realize they got the same random sequence when they pick the same lenses.

Because it is always a random sequence no matter which lenses are used, it turns out there is no way to send any *information* faster than the speed of light. This makes everything compatible with Einstein's relativity. Still super weird, but not faster than light communication.

What about Feynman diagrams? In this article series, I have purposefully avoided math. But quantum mechanics is not only written in math; there are three completely different versions in widespread use: the Schrödinger wave approach, the Dirac formulation, and Feynman's path integrals. The Schrödinger approach emphasizes the waviness of particles and uses differential equations. The Dirac formulation focuses on quantum mechanics' sensitivity to measurement order and uses the language of linear algebra.

Feynman's path integrals also have a wavy point of view, and can be seen as an extension of the Huygens–Fresnel principle of wave propagation. This leads to some truly terrifying path integrals, covering all possible paths and possibilities. Feynman diagrams are a shorthand for keeping track of the approximations you need to make to actually solve things. While the mental models behind the three mathematical traditions are quite distinct, they always give the same answers.

So why are there three equivalent versions of quantum mechanics? Depending on the problem you are worrying about, it turns out that it can be easier to get the answer using one of the three approaches. And physicists are all about using the path of least resistance.

Looking back at this article series, the wavy ideas from the first five articles are usually expressed using the Schrödinger wave approach. But the deterministic and random measurement sets and entanglement we discussed in this article are easier to express using the Dirac approach. The Feynman approach comes into its own at high energies when particles can be created, and the results of particle accelerators like CERN are discussed almost entirely in the language of Feynman path integrals. It is not uncommon for experts to switch from one approach to another mid problem, using whichever approach will get them the right answer with the least pain and suffering (a relative scale, I know).

So when someone claims to have a "new" version of quantum mechanics, I roll my eyes. Not only do they have to correctly predict all the different observations we've seen in this article series, from particle mixing to anti-bunching to entanglement, but we already have *three* versions that work. The new version had better be *useful*, and make it easier to get the right answer.

[Probably leave the next two out, but I wrote them for fun.]

What does instantaneous correlation of entangled particles mean? ¯_(ツ)_/¯ Not my job. As an experimentalist my job is to help figure out <u>how</u> the world works (and hopefully communicate it). <u>Why</u> is the domain of theorists and philosophers. As far as I can tell they haven't a clue, but then again they see me as a knuckle-dragging wrench wielder, so it all evens out.

What about Eve? It is traditional when talking about cryptography to have Alice talking to Bob, with Eve trying to listen in. While Eve is a reference to 'eavesdropping', not the biblical Eve, I tend to think Eve gets a bad rap. As a physicist, the first person to pick from the tree of knowledge is closer to a patron saint than a villain. So I'll leave Eve out of my version of the cryptography story.