The Quantum Eraser

In the orthodox interpretation of quantum mechanics, "measuring" a particular property of a particle does not passively tell you what that property already was. Rather, the act of measurement fundamentally changes the system: the particle's wavefunction collapses into an eigenfunction of that property, and that collapse has tangible effects on the subsequent behavior of the particle.

In this section we're going to talk about the opposite process: "erasing" a measurement, which means eliminating all traces of its result. You did make the measurement, but now there is no way, even in principle, to determine how that measurement came out.

Question: Once you erase the measurement of a particular property, does the particle still have a definite value of that property, even though you don't know what it is? Or does hiding the result negate the effects of the measurement, putting the particle back into a superposition of eigenfunctions with different values?

Answer: Erasing the measurement does, in fact, erase the effect of that measurement. The wavefunction is un-collapsed.

We're going to discuss the quantum eraser in two steps. We will begin with an idealized version, leaving out all the experimental details to focus on the core issues of measurement and erasure. Then we will discuss one real-life experiment and fill in some details about what was actually measured and erased.

Before we get started, a few notes on background reading.

- You probably won't be surprised to learn that all of this will be done in the context of the double-slit experiment. If you're hazy on the details, you may want to refresh yourself on Sections 3.2 and 3.3.
- Through most of this section, we will use the language of the orthodox interpretation of quantum mechanics—the same language we use throughout the book. At the end we will briefly consider how the same experiments look in other interpretations.
- The issue of measurement, the closely related issue of "entanglement," and the idea of different "interpretations" of quantum mechanics, are all discussed in more detail in our online section The Meaning of Quantum Mechanics (www.cambridge.org/felder-modernphysics/onlinesections). You can read either that section or this section without the other, but reading both will deepen your understanding.

Measurement and Erasure

In a double-slit experiment, a particle is sent through a pair of slits and then measured on a back screen some distance behind them. The wavefunction that reaches the back screen is the sum of two different waves, each representing a path through one of the two slits. At different places along the back screen those two waves interfere either constructively or destructively, giving rise to an interference pattern.

The result is completely different if you put in a device that measures which slit the particle passed through. That measurement prevents the two pieces of the wavefunction from interfering with each other, and the alternating pattern on the back screen is destroyed.

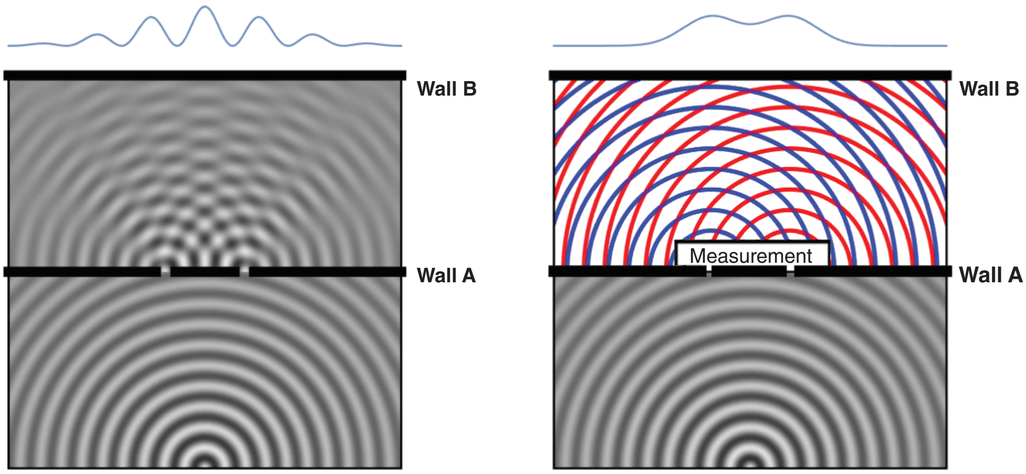


Figure 1 **In an ordinary double-slit experiment (left), the waves from the two slits interfere to create an alternating intensity pattern on the back screen. If you insert a device that allows particles to pass through but measures which slit they go through (right), the interference fringes disappear. Each particle passing through the slits in the measured experiment either generates the wave shown in blue or the one in red, but not both, so there's no interference. Roughly speaking, the result in the un-measured experiment looks like a sine wave of intensity vs. position, while the measured experiment looks mostly like a big blob in the center.**

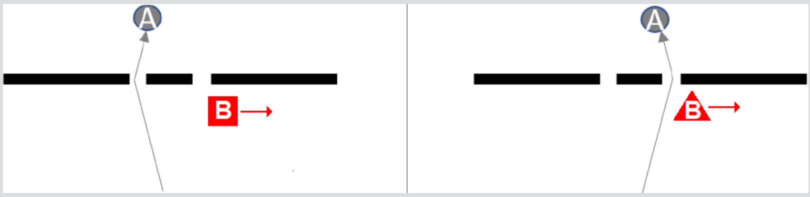
In the orthodox interpretation of quantum mechanics, we say that the measurement of the particle at the slit collapses the wavefunction. The particle acquires a definite position at that moment, going through one slit or the other but not both, so there are no longer two waves to interfere with each other. Other interpretations describe this process differently, but they all agree on the result: if you measure which slit each particle went through, you don't see an interference pattern on the back screen.

Adding a "quantum eraser" to this experiment means that you measure which slit the particle passed through, but then you destroy that information. In the Active Reading Exercise below, you'll consider an idealized version of such an experiment.

Active Reading Exercise: Measurement by Shape

You send Particle A through a double slit. Particle B, passing nearby, has a property that we're calling "squareness."

- If Particle A passes through the left-hand slit, then Particle B remains square.
- But if Particle A passes through the right-hand slit, then Particle B changes to a different property that we're calling "triangleness."



To introduce an important quantum mechanical word, the states of our two particles are now "entangled." There is a 50% probability of finding this system in the state "A went through the left slit and B is square," and a 50% chance of finding "A right slit, B triangle." But there is zero chance of finding the "A left slit, B triangle" state. Each member of an entangled pair of particles is in a superposition of states, but it's a special sort of superposition where a measurement of one of them determines the properties of both.

Particle B now goes flying off in a different direction. But Particle A continues on to the back screen of the double-slit, where you will measure its position. You will then repeat the experiment many times, measuring the positions of many "Particle A"s.

1. After you repeat this experiment many times, is there an interference pattern on the back screen of the double-slit experiment?
2. In an alternative version of the experiment, B flies into an apparatus that changes it into a circle. You never tested it to determine whether it was a square or a triangle, and it is now impossible to recover that information. Is there still an interference pattern on the back screen?

Jot down your answers to those questions before reading on!

1. The first answer is clear: you see a big smudge, with no interference pattern. Even if you send Particle B into deep space and nobody ever looks at it, the fact that it is out there with the stored information about which slit Particle A went through is enough to destroy the interference.
2. In the second case, where B loses its shape before anyone looks, the measurement of which slit Particle A went through is erased, and therefore *you do get an interference pattern on the back screen.* That is not just a theoretical or speculative answer; this experiment has been done, as we will describe below, and the results confirmed that quantum erasure can restore double-slit interference.

As so often happens in quantum mechanics—if that result doesn't bother you, you're not thinking about it hard enough.

The conventional explanation is that Particle B's shape contains information about which slit Particle A passed through, and therefore collapses Particle A's wavefunction; erasing B's shape deletes the information, and therefore un-collapses A's wavefunction. But how did

Particle A's wavefunction "know" that it should un-collapse? A question like that (abstract and philosophical sounding) can sometimes lead you to more concrete questions (that can be tested experimentally). Here are a few that you might come up with.

- What if Particle B travelled several light-years away before losing its shape? Would its loss of information instantaneously cause Particle A's wavefunction to un-collapse? If so, does a quantum eraser provide a mechanism for faster-than-light communication?
- What if Particle B lost its shape *after* Particle A hit the back screen? Would the Particle A accumulation on the back screen still create an interference pattern?

We urge you to think of any other variations you can come up with to explore this idea. Both of the experiments that we just described have been done, and we will discuss their results later in this section. But first we're going to move past the silly "square/triangle" property to describe one way that these experiments were actually performed.

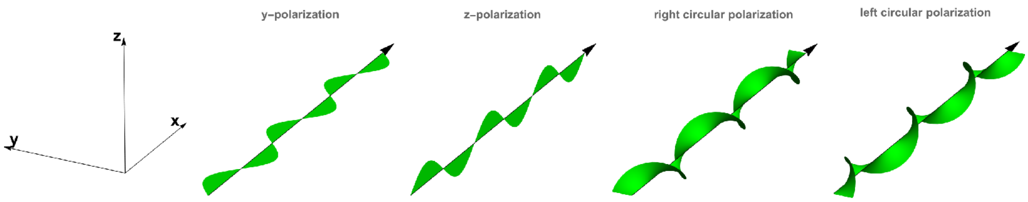
A Digression About Light Polarization

In the particular experiment we're going to describe, the particles were photons (not geometric figures), and the measured property was polarization (not shape). So we need to explain light polarization.

We begin with a purely classical description. Classically, a light beam consists of an oscillating electric field along one axis, and an oscillating magnetic field along a perpendicular axis. Both axes are perpendicular to the direction the wave travels. For instance, if the light beam is moving in the $+x$ direction, then perhaps the electric field is oscillating in the $\pm y$ direction and the magnetic field in the $\pm z$ direction.

The direction the electric field oscillates in is called the "polarization" of the beam. So the example we just described would be said to have y-polarization. Another beam, also traveling in the $+x$ direction, might be polarized in the z direction, or possibly $30°$ from y to z.

But there is also a more complicated option: a light beam can have "circular polarization," meaning the direction of the electric field rotates as the light propagates. (The electric field rotates in a plane, always remaining perpendicular to the direction of motion, and the magnetic field remains perpendicular to both.) Circularly polarized light can be "right circularly polarized" (it rotates clockwise viewed from behind) or "left circularly polarized" (counterclockwise).



Everything we have just said about light polarization would be familiar to 19^{th} century physicists. Now consider a question that those physicists could not have asked: what happens when you measure the polarization of *one photon?* That question, and its answer, make sense only in the realm of quantum mechanics.

The answer is that you have to measure a photon's polarization along a particular set of axes, and what you get depends on what axes you choose. Consider the following series of experiments.

1. *You measure a photon to determine whether its polarization is in the y or z direction.*
   Based on classical physics, you would expect that you might find the polarization along y, or z, or any arbitrary angle in between. But in fact, this measurement has a 50% chance of showing the photon perfectly polarized in the y-direction, and 50% in the z-direction. You will never find anything in between.
2. *You measure the same photon again along the same axes.*
   You are guaranteed to find the polarization pointing along the same axis you found in your first measurement. Repeat the measurement as many times as you like, and you will keep getting the same result. (If that were not true, it would be difficult to argue that your first measurement actually measured anything.)
3. *You then measure its polarization along the lines $z = y$ and $z = -y$: that is to say, at 45° from both axes.*
   Once again, you will find that the polarization is exactly along one of the axes of your measurement. Repeat that measurement and you will get the same result again.
4. *You then measure it again along the y and z axes.* We have arrived at the point we've been building up to this whole time, so pause and ask yourself—what will you find?
   The answer is that you are back to Step 1: you have a 50% chance of finding y-polarization, and 50% of finding z.

In the language of the orthodox interpretation, the measurement along the diagonal axes collapses the particle into an eigenfunction along those diagonal axes. That collapse completely *erases* polarization along the y and z axes, which is why a subsequent measurement in those directions has a 50% chance of finding either one.

In short, a polarization measurement is always along a perpendicular set of axes, and always collapses the photon's state into being polarized along one of those two axes.

If you have read the discussion of spin in Section 7.6, all of that may sound familiar. In any case, that uncertainty relationship—the fact that certain knowledge in a 45° direction implies complete uncertainty along the axes—will be vital in the experiment we're about to describe.

Walborn's Quantum Eraser Experiment

We are now ready to build up, piece by piece, an actual quantum eraser experiment. This experiment was published in 2002 by Walborn, et al.[1]

Below we describe Walborn's experiment as it acted on one individual photon. But keep in mind that, in order to observe whether or not there's an interference pattern, he had to send many such photons through the apparatus. Also, by the way, we will consistently treat the

1 Walborn, S. P., Terra Cunha, M.O., Padua, S., and Monken, C.H. (2002). "Double-Slit Quantum Eraser". Phys. Rev. A. 65 (3): 033818. arXiv:quant-ph/0106078.

direction of motion as the $+x$ direction, so remember that the polarization must always be perpendicular to that.

Step 1: A Nonlinear Crystal Creates Anticorrelated Polarizations

Walborn's apparatus began by sending each photon through a device called a "nonlinear crystal." Such a crystal splits one photon into two different photons, which we will call A and B. Each photon is in a superposition of y and z polarization, but their polarizations are "anti-correlated." If you measure their polarizations along the y and z axes, you are guaranteed to find one of the following two states.

- A is polarized in the y-direction, and B in the z-direction. (Probability 1/2)
- A is polarized in the z-direction, and B in the y-direction. (Probability 1/2)

There is NO chance of finding them with the same polarization. The states of the two photons are entangled, so a measurement of either photon's polarization determines both photons' polarizations.

After Walborn's two photons left the crystal in their anti-correlated state, he sent Photon A through the two slits of a double-slit experiment, and Photon B off in another direction.

We're going to ask essentially the same question at each phase of the process: *If that were the whole experiment, would you expect Walborn to see an interference pattern, or not?* Pause and ask yourself that question at this stage. Will the wavefunction of Photon A pass through both slits and then interfere with itself?

The answer is yes: if our description above were the entire experiment, then Walborn would have gotten an interference pattern on the back screen. The polarizations of A and B could be measured, but such a measurement would not convey any information about which slit A went through. So the polarization is irrelevant at this stage.

Step 2: A Quarter-Wave Plate Changes Linear Polarization Into Circular Polarization

Photon B is now heading off toward a different apparatus, but let's follow Photon A as its wavefunction propagates outward and passes through the two slits. Just beyond each slit, Walborn placed a "quarter-wave plate": a device that changes linearly polarized light into circularly polarized light. But the two devices had opposite orientations.

- The plate in front of Slit 1 changed y polarization to left circular polarization, and z polarization to right circular polarization.
- The plate in front of Slit 2 changed y polarization to *right* circular polarization, and z polarization to left circular polarization.

Figure 2 shows the effects of both plates in the case where Photon A enters with y-polarization.

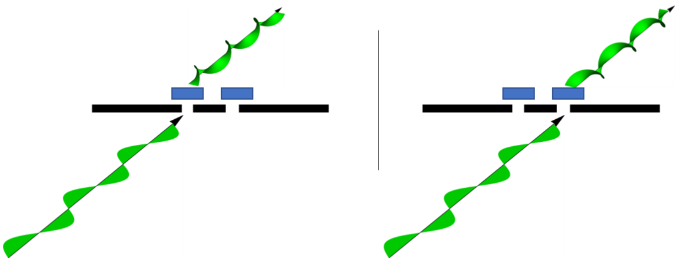


Figure 2 **Quarter wave plates placed in front of each slit turned y polarized light into either left circularly polarized light (left slit) or right circularly polarized light (right slit).**

But remember that Figure 2 doesn't tell the whole story; it only shows what happens to an incoming Photon A that happens to be y-polarized. In Walborn's experiment, every Photon A had a 50/50 chance of being y or z polarized, and was paired with a Photon B that had the opposite polarization.

That's a lot of photons, devices, and polarizations to keep track of. So pause for a moment to make sure you can follow in Figure 3 the four states of the system after Photon A passed through the quarter-wave plates just past the slits. Then check yourself with the Active Reading Exercise below.

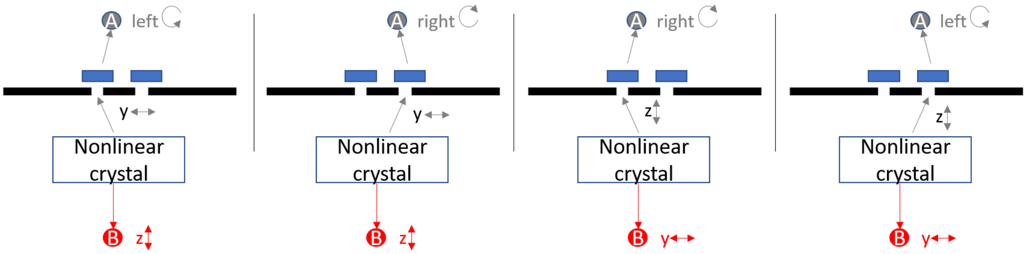


Figure 3 **After Photon A passed through the quarter-wave plates, the entire system was in a superposition of the four states shown here.**

Active Reading Exercise: Measurement by Polarization

Imagine that you are doing Walborn's experiment, as described above.

1. Suppose you measure that Photon A reaches the back screen right-polarized, and Photon B is z-polarized. Can you conclude that Photon A went through the left-hand slit, or can you conclude that it went through the right-hand slit, or do you not have enough information to determine what slit it went through?
2. Now suppose you send many photons through this system, but you never measure their polarizations, so each system remains in a superposition of the four states shown in Figure 3. Would the A photons create an interference pattern? Why or why not?
3. Finally, suppose you measured each Photon B to determine if it was y or z-polarized. Would that measurement change your answer to Part 2? Explain.

1. Photon A went through the right-hand slit. You can check that just by looking at the four pictures in Figure 3. A bit more painfully (but perhaps more satisfyingly), you can step through the process. If B is z-polarized, then A must have been y-polarized. That means the left-hand slit would give A left circular polarization, the right-hand slit would give it right. Since you measured A with right circular polarization, it went through the right-hand slit.
2. As we just discussed, a simultaneous measurement of A's *and* B's polarizations could determine what slit A went through. The information exists, which means A went through one slit or the other—not through both. Therefore there is no interference pattern.

3. Measuring whether B is y or z polarized wouldn't change the result. Whether you measure B's polarization or not, the interference pattern is still gone because the information is out there. Since you *could* do a measurement to find which slit A went through, there's no interference whether you do that measurement or not.

We're almost at the final, critical step. But if you have (quite understandably) zoned out by this point, have a cup of coffee and then re-read up to this point. The punch line won't hit home if you're not clear on how Walborn's differently aligned quarter-wave plates constituted a measurement that destroyed his interference pattern.

Step 3: A Diagonal Measurement of B's Polarization Erases Its Original Polarization Information

We've been following Photon A through the double-slit experiment. But what happened to Photon B during all this?

Photon B now entered an apparatus that measured its polarization—not along the y and z axes, but at a 45° angle from both axes. That measurement put B into a state of definite polarization along either the line $z = y$ or along the line $z = -y$. Because of the entanglement, that put A into the other state, perpendicular to B's polarization.

But as we discussed above, a state of definite polarization at a 45° angle between y and z is a state of *no information* about polarization along the y or z axis. So when A encountered the plates just past the slits, it was equally likely to end up left or right circularly polarized, no matter which slit it went through. The diagonal measurement of B erased the information about which slit A went through.

And now, we ask our recurring question one last time. After he erased the polarization of B along the y and z axes, would you expect Walborn's A photons to build up an interference pattern, or not?

The Results, and Why You Can't Use a Quantum Eraser to Communicate Faster than Light

Walborn and his collaborators did the experiment as we described it above. They prepared the anti-correlated photons, put the A photons through the double-slit apparatus with the quarter-wave plates, and performed the diagonal polarization measurement on Photon B.

The result, as we hope you correctly guessed, is that they did indeed see an interference pattern.

We'll explain in a moment one final detail of how they did that last measurement. But don't let the details distract you from the main process:

- If you do this experiment without inserting the oppositely aligned quarter-wave plates, you get an interference pattern. (The polarization in this case doesn't matter, because it is not correlated in any way with *which slit* Photon A went through. So this is just the original double-slit experiment described in Sections 3.2 and 3.3.)
- If you insert the oppositely aligned quarter-wave plates, that *creates information*—the polarization of both photons contains enough information to determine which slit Photon A went through—so you no longer get an interference pattern.

- But if you then perform a diagonal measurement of B, that *erases that information,* and you get an interference pattern again.

Those three facts are the core information; everything else is the details.

But coming back to those details, we are now ready to discuss some of the variations we brought up earlier. To start with: can you use Walborn's experiment to communicate faster than light? Of course the answer must be "no," but why not? Consider the following scheme.

1. You set up an experiment like Walborn's, but in your version, the photons travel a light year in opposite directions.
2. Your accomplices (in space) do the measurements on all the B photons, just before you (on Earth) watch all the A photons hit the back screen.
3. If your partners want to tell you to bet on the Vulcan football team, they measure B along the y and z axes—or maybe they don't measure B at all. The point is that B contains enough information to determine which slit A went through, so you don't see interference.
4. If they want to tell you to bet on the Romulan team, your partners measure B diagonally. That makes the interference pattern appear on your screen.
5. The result is that you find out instantaneously the results of the game, while everyone else on Earth has to wait years to get the same result. So you place your bet and get filthy rich!

As you know, relativity always forbids such superluminal information transfer. (In someone else's reference frame, you would wind up placing your bet before the game even happened!) In this particular case, you would wind up seeing a no-interference-pattern blur no matter what your partners did. To explain why, we need to pick up one final detail of Walborn's experiment.

Each time Walborn sent a photon through this experiment, he ended up with two pieces of information. One piece was, of course, the spot where Photon A hit the back screen. The other piece was the polarization of Photon B: either it was along the line $z = y$, or else along the line $z = -y$.

Walborn did not look for a pattern caused by all of the A photons together. Rather, he divided the A photons into two groups: the ones paired with "$z = y$" B photons, and the ones paired with "$z = -y$" B photons. Each of those groups, separately, created a clear interference pattern on the back screen.

But these two interference patterns were offset from each other on the back screen. The peaks of one showed up in the troughs of the other. So when he looked at the two of them together on the screen, he saw the same big blur that he would have seen without the diagonal measurement. Only by keeping track of which A-spots on the screen paired with which B-polarizations did Walborn map out an interference pattern.

You can go through the calculations to show why the two patterns must be offset in that way, but we're not going to do that here. We are going to point out that they *must* be offset in precisely this way, if only to prevent the faster-than-light communication described above. If your accomplices measure each Photon B diagonally, you will still see a no-interference blur. You can't sort out that blur until they tell you which B photons were which, and that will take a few years.

The Delayed Choice Quantum Eraser

Earlier in this section, we mentioned two particularly problematic variations of this experiment. The first was the variation we just discussed: putting a long distance between you and your partners. In more precise language we could say that we discussed the two events, "Photon B is measured" and "Photon A hits the back screen," having a *spacelike separation*. No information can be transferred between two such events.

Our other proposed scenario is the opposite in some ways, because it involves a timelike separation. Imagine that you run Walborn's experiment, but you allow all the A photons to hit the back screen *before* you diagonally measure the B photons. Will the A photons still build up an interference pattern?

The answer is yes. The answer *must* be yes. Your measurement erased the information that B was carrying about y-polarization, so it erased the information about which slit A went through, so you see interference.

To understand what this looks like, remember the point we made above: the total of *all the A photons together* does not create an interference pattern. What builds up on your back screen is just a blur. (Of course it's a blur; you haven't measured B yet!) Now you do your diagonal measurements of B photons, and you label each one as a $z = y$ photon or a $z = -y$ photon. Walborn did just this experiment. Then he looked back at the blur on his screen, and sorted the A photons based on what B photons they were paired with. As quantum mechanics predicts, when he looked at only the A photons that were paired with the $z = y$ collection of B photons, those photons described an interference pattern.

Other groups have performed a "delayed-choice quantum eraser" experiment. In this version of the experiment, not only does the measurement of B happen after the measurement of A, but even the decision of whether to measure B along the axes or along the diagonals is made after A reaches the back screen. (It's typically done by using another random quantum event to "decide" since the experiments are too fast for a human to make the decision in real time.) As quantum mechanics predicts, the delayed decision has no effect on the outcome; for the cases where the measurement was along the diagonals, the "$z = y$" A photons sort themselves into an interference pattern, and so do the "$z = -y$" A photons. For the cases where the measurement was along the axes, there was no interference pattern.

Conclusions

There is nothing inherently contradictory about quantum mechanics. The equations make predictions, and the predictions work. The results of Walborn, and of the many others who have performed quantum eraser experiments, are perfectly consonant with the predictions made by the theory.

But you run into a problem when you try to describe a causal sequence of events. That problem occurs with all of the experiments we described here, but it is perhaps sharpest in the delayed choice version. How do all the A photons align themselves according to B measurements that have not yet been made, and may never be made at all? In one form or another, you always seem to wind up concluding that an event in the future *caused* an event in the past.

Some physicists argue that these problems are not inherent to quantum mechanics. Rather, they say, these problems arise from the orthodox interpretation of quantum mechanics, which postulates that measurement collapses the wavefunction.

In our online section The Meaning of Quantum Mechanics (www.cambridge.org/felder-modernphysics/onlinesections) we discuss two alternative interpretations, Many-Worlds and Pilot-Wave. Both of these interpretations reject the idea that the wavefunction collapses when measured. Some proponents of those interpretations have written that quantum eraser experiments are overhyped. All that's happening throughout the process is a steady evolution of the system according to the time-dependent Schrödinger equation, and the results are just what that equation predicts. Why does the interference pattern disappear when you measure which slit Photon A went through? Because that measurement puts those two branches of the wavefunction out of phase in an unpredictable way, thus ruining the alternating pattern of constructive and destructive interference you would have had without the measurement. But if you carefully undo the effects of that phase shift, you recover an interference pattern. There's no collapse to reverse, and certainly no causality going backwards in time.

As we stress in our comparison of these interpretations, all three of them make the same predictions for experiments, so there is no empirical way to select one of them as right—for now. But one thing we hope you have gotten from reading about the quantum eraser is that many questions, questions that might sound hopelessly abstract at first, can be tested by sufficiently clever experiments. Some theorists are still working to find experiments that will sort out what is actually going on, underneath the quantum covers.