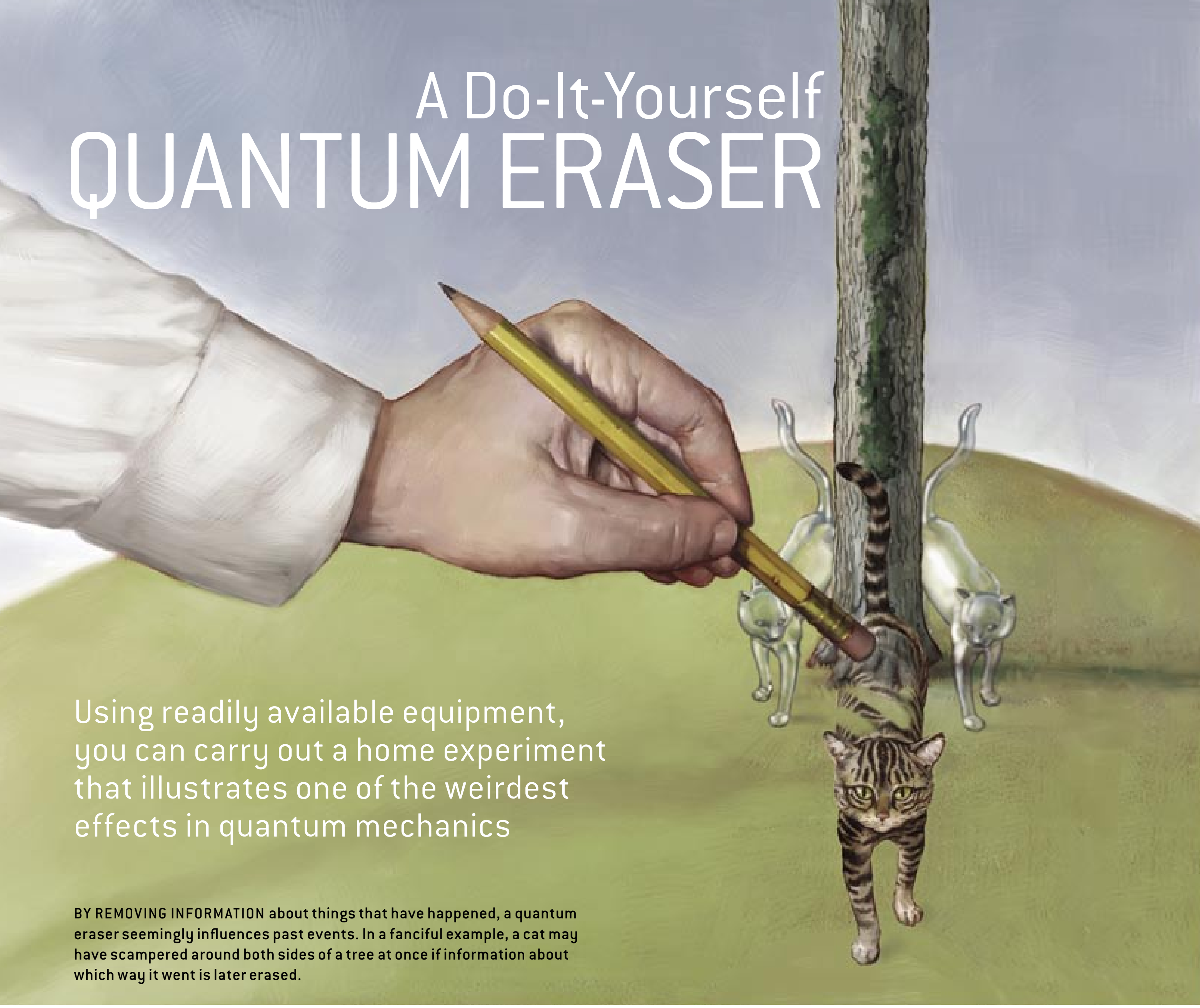


A Do-It-Yourself QUANTUM ERASER

Using readily available equipment, you can carry out a home experiment that illustrates one of the weirdest effects in quantum mechanics

BY REMOVING INFORMATION about things that have happened, a quantum eraser seemingly influences past events. In a fanciful example, a cat may have scampered around both sides of a tree at once if information about which way it went is later erased.

MATT COLLINS

BY RACHEL HILLMER AND PAUL KWIAT

Notoriously, the theory of quantum mechanics reveals a fundamental weirdness in the way the world works. Commonsense notions at the very heart of our everyday perceptions of reality turn out to be violated: contradictory alternatives can coexist, such as an object following two different paths at the same time; objects do not simultaneously have precise positions and velocities; and the properties of objects and events we observe can be subject to an ineradicable randomness that has nothing to do with the imperfection of our tools or our eyesight.

Gone is the reliable world in which atoms and other particles travel around like well-behaved billiard balls on the green baize of reality. Instead they behave (sometimes) like waves, becoming dispersed over a region and capable of crisscrossing to form interference patterns.

Yet all this strangeness still seems remote from ordinary life. Quantum effects are most evident when tiny systems are involved, such as electrons held within the confines of an atom. You might know in the abstract that quantum phenomena underlie most modern technologies and that various quantum oddities can be demonstrated in laboratories, but the only way to see them in the home is on science shows on television. Right? Not quite.

On pages 92 and 93, we will show you how to set up an experiment that illustrates what is known as quantum erasure. This effect involves one of the oddest features of quantum mechanics—the ability to take actions that change our basic interpretation of what happened in past events.

Before we explain what we mean by that and outline the experiment itself, we do have to emphasize one caveat in the interest of truth in advertising. The light patterns that you will see if you conduct the experiment successfully *can* be accounted for by considering the light to be a classical wave, with no quantum mechanics involved. So in that respect the experiment is a cheat and falls short of fully demonstrating the quantum nature of the effect.

Nevertheless, the individual photons that make up the light wave are indeed doing the full quantum dance with all its weirdness intact, although you could only truly prove that by sending the photons through the apparatus and detecting them one at a time. Such a procedure, unfortunately, remains beyond the average home experimenter. Still, by observing the patterns in your experiment and by thinking about what they mean in terms of the individual photons, you can get a firsthand glimpse of the bizarre quantum world.

If you want to go straight to the home experiment, it is detailed on the next two pages. The discussion that follows here (and continues on page 94) delves into the science of quantum erasers in general. This explanation will help you understand what the do-it-yourself eraser demonstrates, but you might want to come back to it after seeing what that specific kind of eraser does.

What a Quantum Eraser Erases

ONE OF THE STRANGE FEATURES of quantum mechanics is that the behavior that something exhibits can depend on what we try to find out about it. Thus, an electron can behave like a particle or like a wave, depending on which experimental setup we subject it to. For example, in some situations particlelike behavior emerges if we ascertain the specific trajectory that an electron has followed and wavelike behavior transpires if we do not.

A standard demonstration of this duality relies on what is called a two-slit experiment (your do-it-yourself quantum eraser is similar to this experiment in that it involves two pathways, but not two slits). A source emits particles, such as electrons, toward a screen that has two slits they can pass through. The particles ultimately arrive at a second screen where each one produces a spot. Where each particle lands is to some extent random and unpredictable, but as thousands of them accumulate, the spots build up into a definite, predictable pattern. When the conditions are right for the particles to behave as waves, the result is an interference pattern—in this case a series of fuzzy bars, called fringes, where most of the particles land, with very few hitting the gaps between them.

The particles will generate the interference pattern only if each particle could have traveled through either of the two slits, and there is no way of ascertaining which slit each one passed through. The two pathways are then said to be indistinguishable and each particle acts as if it actually traveled through both slits. According to the modern understanding of quantum mechanics, interference occurs when indistinguishable alternatives are combined in this way.

When two or more alternatives coexist, the situation is called a superposition. Erwin Schrödinger highlighted the oddity of quantum superpositions in 1935, when he proposed his now infamous concept of a cat that is simultaneously alive and dead, sealed inside a hermetic box where it cannot be observed. When quantum interference happens, something in the experiment is like a kind of Schrödinger's cat. But instead of being alive and dead at the same time, the cat may be walking by a tree, passing on both sides of it simultaneously.

Schrödinger's cat ceases to be in a superposition as soon as we look inside its box: we always see it to be either alive or dead, not both (although some interpretations of quantum mechanics have it that *we* become in a superposition of having seen a dead or a live cat). If a spotlight is shining near the tree, we see the quantum cat go one way or the other. Similarly, we can add a measurement tool to watch each particle as it passes the slits. One could imagine having a light shining on the slits so that as each particle comes through we can see a flash of light scatter from where the particle went. The flash makes the two alternative pathways distinguishable, which destroys the superposition, and the particles arrive at the final screen not in a pattern of fringes but in one featureless blob. Experiments analogous to this scenario have been conducted, and, as predicted by quantum mechanics, no interference pattern builds up.

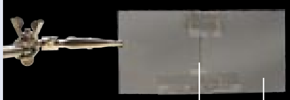
We need not actually "do the looking." We do not have to

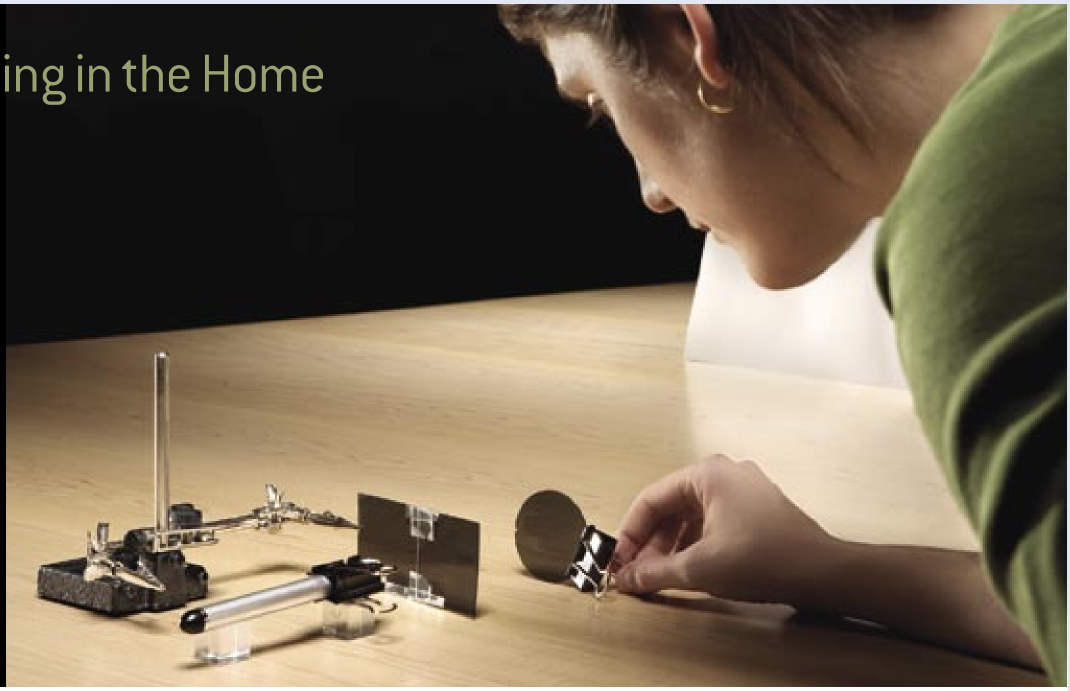
What you will need for the experiment

- **A very dark room.**
- **Polarizing film.** Plain gray, high-quality film ("experimental grade") gives the best results; avoid film tinted with a color (see www.sciam.com/ontheweb for some places that sell film). You need to cut it into six squares, each about two inches on a side. The box on page 94 describes what polarizers do to photons.
- **A laser,** such as a laser pointer. If yours emits polarized light, align its polarization at 45 degrees from the vertical. If your laser is not polarized, include a polarizer at 45 degrees immediately after the laser at every step. Use a rubber band to keep the laser turned on.
- **A thin, straight piece of wire,** such as from an unused twist tie or a straightened staple. The thinner the better.
- **Some tinfoil and a pin** to poke a hole in it. The light that goes through the pinhole will expand outward, forming a narrow, conical beam. The pinhole makes the patterns dimmer but may improve the results if the room is dark enough.
- **Some stands** to hold the laser and polarizers in place. These could be as low-tech as cereal boxes.
- **A screen** to display the final patterns. The bare wall will do if it is plain enough; otherwise use a sheet of paper.

Quantum Erasing in the Home

The steps presented here outline how to see quantum erasure in action. See www.sciam.com/ontheweb for a fuller description and additional information, such as the basics of how waves interfere and produce fringes.

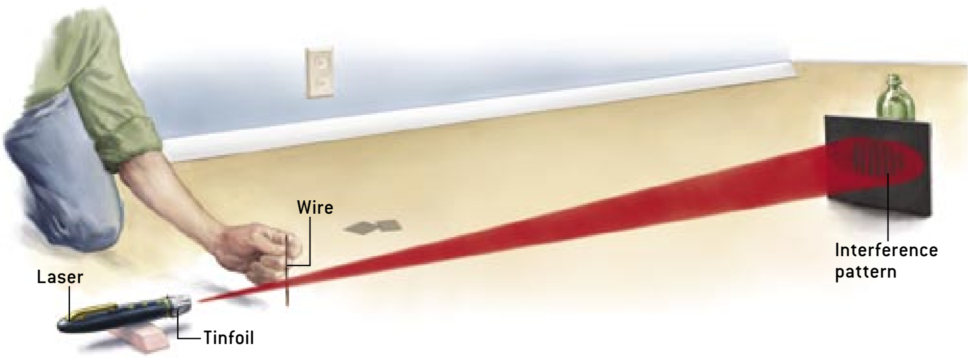


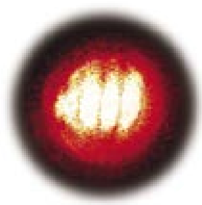


1 SEEING INTERFERENCE

- Wrap the tinfoil around the business end of the laser and put a pinhole in it to let through some of the light beam.
- Set up the laser so it shines on the screen from at least six feet away. It should produce a circular spot of light on the screen.
- Position the wire vertically and centered in the light.

WHAT HAPPENS: As shown, you should see an interference pattern consisting of a row of fringes (bright and dark bands). The interference pattern arises because light passing on the left of the wire is combining, or "interfering," with light passing on the right-hand side. If you hold a piece of paper just after the wire, you will see a lobe of light on each side of the shadow of the wire. The lobes expand and largely overlap by the time they reach the screen. For each individual photon arriving at the screen in the overlap region, it is impossible to tell whether it went on the left or the right side of the wire, and the combination of the two ways it went causes the fringes. Although you are looking at trillions of photons, each of them is interfering only with itself.



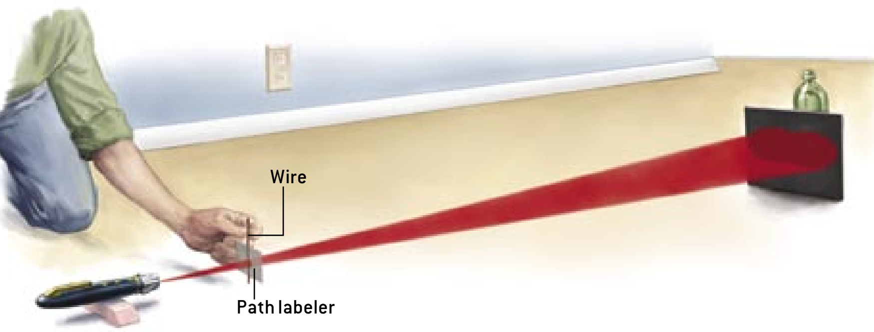


INTERFERENCE seen is captured in this photograph. The size and other features of the patterns depicted in the diagrams are exaggerated.

2 LABELING THE PATH

- Take two polarizers and rotate one of them so that their axes are perpendicular; you have done this correctly if when you overlap the film temporarily, no light goes through the overlap region.
- Tape them together side by side with no gap or overlap. Do the taping along the top and bottom so the tape will not block the light. We will call this the path labeler.
- Position the labeler in the beam so that its join is right behind the wire. Attaching the wire to the labeler might be easiest. Wire and labeler will not be moving for the rest of the experiment. We will say that the left-hand polarizer produces vertically polarized light (V), and the right-hand one horizontally polarized (H). It does not matter if we have these labels reversed.

WHAT HAPPENS: Even though the light is again passing on both sides of the wire, the fringes should be gone. If a photon reaches the screen by passing to the left of the wire, it arrives V-polarized; if to the right of the wire, H-polarized. Thus, the labeler has made available the information about which way each photon went, which prevents the interference.

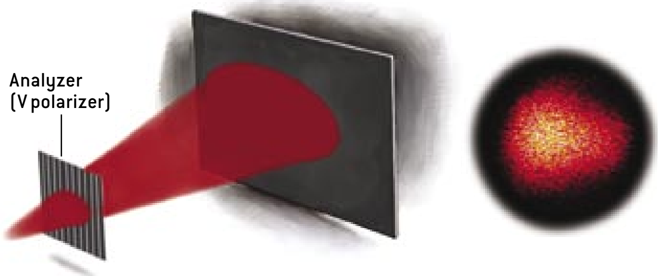


RACHEL HILLMER (*photographs of light patterns*); BRIAN MARANAN PINEDA (*laser setup*); MATT COLLINS (*drawings of setups and cat*)

3 SELECTING THE LEFT-PASSING PHOTONS

- Position a third polarizer (the "analyzer") between the labeler and the screen in the V orientation.

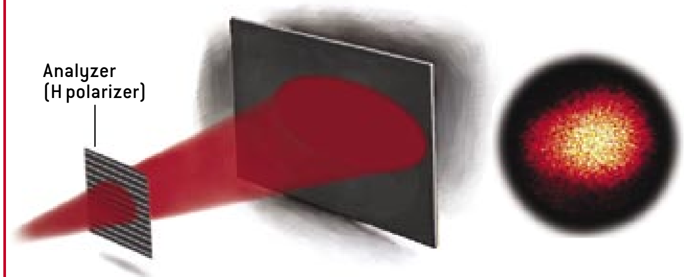
WHAT HAPPENS: The analyzer will block all the right-passing photons (which became H-polarized at the labeler) and will let through all the left-passing ones. The pattern will be nearly the same as in the previous step—just dimmer and not extending quite so far on the right, because it is only the left lobe of light. With the analyzer, you are accessing the information that the labeler made available: you know that all the photons hitting the screen passed to the left of the wire.



4 SELECTING THE RIGHT-PASSING PHOTONS

- Put the analyzer in the H orientation.

WHAT HAPPENS: The H analyzer blocks the left-hand lobe of light and lets through only the right-hand lobe. If you could measure intensities of light (or numbers of photons) at the screen, you would find that the light in step 2 was just the sum of the light in steps 3 and 4. Notice that the fringes were missing from step 2 even though you were not ascertaining the polarization of the photons; it was enough that you could have done so, as in steps 3 and 4.



5 ERASING THE PATH INFORMATION

- Rotate the polarizer 45 degrees clockwise from V, an orientation we call diagonal (D).

WHAT HAPPENS: The fringes reappear! Why? The polarizer is erasing the information about which side each photon used. Now each left-passing V photon has a 50 percent chance of getting through it to the screen, as does each right-passing H photon. In both cases, the photons that get through become D-polarized, so there is no way to tell which way each photon went. Once again, each photon apparently goes both ways at once and interferes with itself.

6 THE ANTI-ERASER

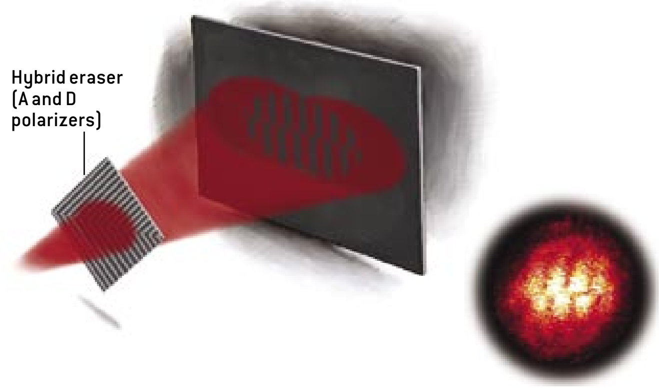
- Rotate the polarizer 45 degrees counterclockwise from V ("antidiagonal" or "A").

WHAT HAPPENS: Again there are fringes—everything said in step 5 applies to an A-polarized eraser as well. But if you look very closely, you will see that the fringes are shifted slightly in the two cases. The A fringes are bright where the D ones are dark, and vice versa. If you could add up the intensities, or numbers of photons, for the D and A erasers, the sum would again be the shape from step 2, with no interference visible.

7 BOTH ERASERS AT ONCE

- Cut in half horizontally a D-oriented and an A-oriented polarizer.
- Join the top half of the D with the bottom half of the A.
- Put the hybrid analyzer in place.

WHAT HAPPENS: D fringes appear in the top half of the light and A fringes in the bottom half. The pattern looks a bit like misaligned teeth and makes clearer how the dark and bright fringes of each eraser correspond.



CONCLUSION

Think about what the photons were doing in each of the steps.

- In some steps (*3* and *4*), each photon went on one side or the other of the wire (no interference), but in others (*1, 5, 6* and *7*), they seemingly went on both sides at once (producing interference).
- Our interpretation of what the photons did at the wire depends on what they encountered *later on* in the setup—be it an analyzer or an eraser or nothing but the screen.
- Steps 6 and 7 revealed that the "which way?" information can be erased in more than one way, to produce either the original interference pattern or the inverse of it.

What polarizers do to photons

Polarizing film has an axis (in our diagrams we depict its direction with lines on the film), and the film allows passage of light that is oscillating parallel to the axis. You can think of light as being like a wave on a rope held between two people; the wave can make the rope move up and down or side to side or at any angle in between. The angle of the oscillation is the polarization of the wave.

Polarizing film is like a screen of parallel bars that the rope passes through: it lets through waves polarized parallel to it unhindered, blocks perpendicular ones completely and allows waves on other angles to get through with reduced amplitude. Most important, the wave (if any) that comes out the other side of a polarizer is polarized parallel with the polarizer's transmission axis.

The quantum description of what happens to light going through a polarizing film sounds only slightly different: The light is made up of individual particles called photons, and like a wave, the photons can each have a direction of oscillation. A photon will get through every time when it hits a polarizer with the transmission axis parallel to the photon's polarization. A perpendicular polarizer blocks the photon every time. At a 45-degree angle, the photon has a 50 percent chance of getting through (the exact probability varies as the angle is varied). Most important, when a photon does go through a polarizer, on the other side it will be polarized parallel with the polarizer's transmission axis.

Light can also be unpolarized, which means the photons making up the light have random polarizations. That is another case in which half the photons will get through a polarizer, and, as always, those that do so become polarized parallel with the polarizer.

You can see how polarizers work by putting two of them together. As you rotate one of the polarizers, you can see through them clearly when their axes are aligned, barely at all when they are perpendicular and to some extent at other angles. Photons that make it through the first polarizer are polarized by it, and then their probability of getting through the second one depends on the angle between their polarization and the second polarizer's axis.

An interesting effect happens if two polarizers are perpendicular and a third one is inserted between them on an angle (45 degrees is best): adding the third polarizer allows some light to get through, even though you might expect it to be an additional obstacle for the light. See if you can explain why that happens (the answer is at www.sciam.com/ontheweb). The do-it-yourself quantum eraser also relies on a polarizer at 45 degrees changing what the light does.

detect the light flashes and ascertain which way each particle went. It suffices that the information is available in the flashes and *could* have been observed in that way.

Now we finally get to the quantum eraser. The eraser is something that can erase the information indicating which path each particle has followed, thereby restoring the indistinguishability of the alternatives and restoring interference.

How might an eraser do that? Imagine that the "flash of light" that scatters from each particle is a single photon. For the photon to reveal the "which path?" information of the particle, it must be possible (even if only in principle) to tell which slit the photon came from. That means we must be able to measure the position of where each photon scattered accurately enough to tell the slits apart. Heisenberg's uncertainty principle, however, tells us that if we instead measure the momentum of each photon with great accuracy, then the photons' positions become less well defined. So if we pass the photons through a lens that makes their momentum information available, the information about their positions is erased. When that happens, the two paths the particles can follow are again indistinguishable and interference is restored.

We have omitted one last tricky detail, but we will come back to that. First, stop and think a bit more about what is happening in the erasing process we just described, because that is where the weirdness lies. When we detect the position where one of the photons scattered, we learn which slit its corresponding particle went through, which means the particle *did* go through one slit or the other, not both. If we instead detect the photon's momentum, however, we cannot know which slit the particle went through. What is more, when we do many momentum measurements and see an interference pattern, we infer that in those cases the particles went through both slits (interference would be impossible otherwise).

In other words, the answer to the question, "Did the particle go through one slit or both slits?" depends on what we do with its corresponding photon long *after* the particle has gone through. It is almost as if our actions with the photons influence what has happened in past events. We can find out which slit the particle went through, or with our quantum eraser we can delete that information from the universe.

Strangest of all, we can decide which measurement to make *after* the particle has passed through the slits—we can have the apparatus for both alternative measurements in place, with a switch that we flick one way or the other just before each pho-

THE AUTHORS

RACHEL HILLMER and *PAUL KWIAT* are both at the University of Illinois, where Hillmer is an undergraduate student in Kwiat's laboratory. Kwiat is Bardeen Chair in Physics, and his research includes the phenomena of quantum interrogation and quantum erasure, optical implementations of quantum information protocols and nonquantum studies of swing dancing. Hillmer is working on novel ways to encode quantum information in light.

BRIAN MARANAN PINEDA

ton arrives. Physicists call this variation a delayed-choice experiment, an idea introduced by John A. Wheeler of the University of Texas at Austin in 1978 that extends a scenario that Niels Bohr and Albert Einstein used in their arguments about quantum mechanics and the nature of reality in 1935.

At this point, some particularly clever readers will be worrying about a fundamental problem that seems to undermine what we have just described: Why can't we delay the choice of our photon measurement until after we have seen if the particles form an interference pattern? We could, in fact, arrange to do just that by having the final screen not too far from the slits and the photon detector much farther away. So what would happen if we saw the particles form fringes but then chose to do photon position measurements that should prevent such fringes from forming? Wouldn't we have created a paradox? Surely we would not expect the already registered interference pattern to vanish! Similar reasoning suggests we could use the delayed-choice effect to transmit messages instantaneously over arbitrary distances (thereby circumventing the speed of light).

That tricky detail that we omitted earlier is what saves the day: to see the interference of the particles after applying the quantum eraser, we first have to divide them into two groups and observe the groups separately. One group will display the original pattern of fringes; the other will display the inverse of that pattern, with particles landing on what were originally the dark bands and avoiding the places where the bright fringes were. The two groups combined fill in all the gaps, hiding the interference.

The paradox is avoided because we need data from the photon measurement to know which group each particle belongs to. Thus, we cannot observe the fringes until after we have done the photon measurements, because only then do we know how to split the particles into groups. In the home experiment, dividing particles into groups is done for you automatically because one group gets blocked by a polarizing filter, and you can therefore see the interference pattern of the group that gets through with your own eyes. In the final step you can see the interference patterns of the two groups right next to each other.

From a practical standpoint, the inability to send messages faster than the speed of light and create a paradox is perhaps disappointing, but physicists and logicians consider it to be a very good feature. SA

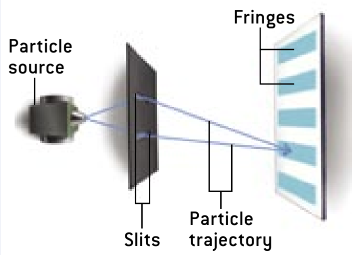
For more discussion about quantum erasers, go to ***www.sciam.com/ontheweb***, where you will find:

- A list of cutting-edge interference and quantum eraser experiments carried out in recent years.
- A short discussion of what quantum erasers have to do with how the ordinary world we are familiar with emerges from the weird underlying quantum reality.
- More information about delayed-choice experiments and the impossibility of superluminal messages.
- A few other related experiments you can do at home.

How a Quantum Eraser Works

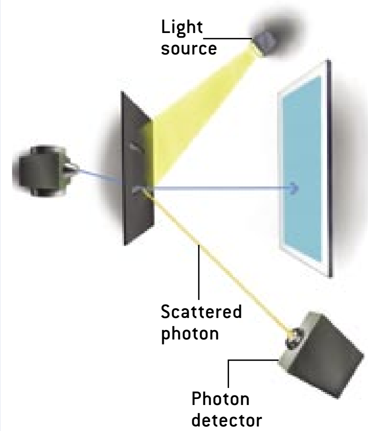
How quantum particles behave can depend on what information about them can possibly be accessed. A quantum eraser eliminates some information and thereby restores the phenomenon of interference. The eraser's action is most easily understood by considering a "double-slit" experiment (*below*).

CREATING QUANTUM INTERFERENCE



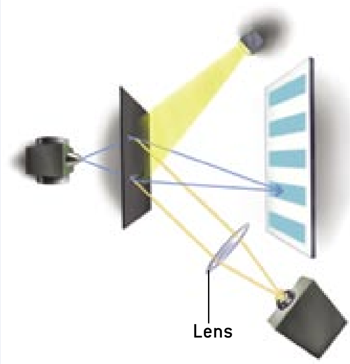
Particles sent through two slits generate bands (called fringes) on a detector screen when large numbers arrive at some regions (*blue*) and very few arrive at other regions (*white*). This interference pattern arises only if each particle could have traveled through both slits to arrive at the screen (*arrows*).

PREVENTING INTERFERENCE



The fringes do not appear if the particles interact with something that could thereby be used to ascertain each particle's location at the slits. For example, a photon of light (*yellow line*) might scatter from the particle and reveal that it went through the right-hand slit. The photon need not be detected—all that matters is that the "which slit?" information in principle could be determined if it were to be detected.

ERASER RESTORES INTERFERENCE



A quantum eraser erases the "which slit?" information. If the particle scatters a photon, a lens could make it impossible to ascertain which slit the photon came from. In that case, the corresponding particle apparently goes through both slits, as before, and fringes can be observed. The strangest feature of this quantum erasing is that the behavior of the particle at the slits seemingly depends on what the photon encounters *after* the particle has passed through the slit(s).

MATT COLLINS