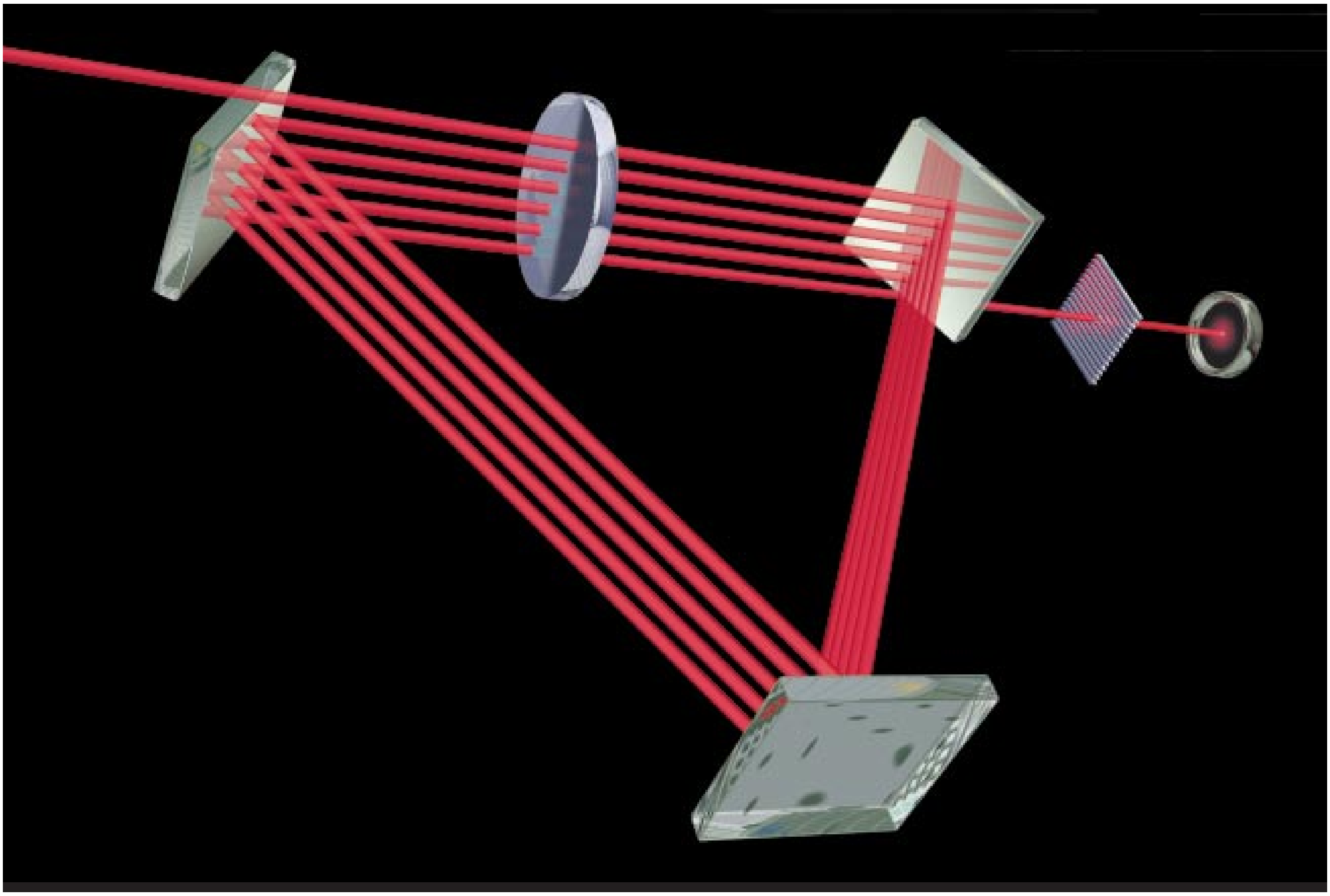


MICHAEL GOODMAN

Quantum Seeing in the Dark

Quantum optics demonstrates the existence of interaction-free measurements: the detection of objects without light—or anything else—ever hitting them

by Paul Kwiat, Harald Weinfurter and Anton Zeilinger

In Greek mythology, the hero Perseus is faced with the unenviable task of fighting the dreaded Medusa. The snake-haired beast is so hideous that a mere glimpse of her immediately turns any unlucky observer to stone. In one version of the story, Perseus avoids this fate by cleverly using his shield to reflect Medusa's image back to the creature herself, turning *her* to stone. But what if Perseus did not have well-polished armor? He presumably would have been doomed. If he closed his eyes, he would have been unable to find his target. And the smallest peek would have allowed some bit of light striking Medusa to reflect into his eye; having thus "seen" the monster, he would have been finished.

In the world of physics, this predicament might be summed up by a seemingly innocuous, almost obvious claim made in 1962 by Nobelist Dennis Gabor, who invented holography. Gabor asserted, in essence, that no observation can be made with less than one photon—the basic particle, or quantum, of light—striking the observed object.

In the past several years, however, physicists in the increasingly bizarre field of quantum optics have learned that not only is this claim far from obvious, it is, in fact, incorrect. For we now know how to determine the presence of an object with essentially no photons having touched it.

Such interaction-free measurement seems to be a contradiction—if there is no interaction, how can there be a measurement? That is a reasonable conundrum in classical mechanics, the field of physics describing the motions of footballs, planets and other objects that are not too small. But quantum mechanics—the science of electrons, photons and

LASER BEAM following a spiraling path that leads to a photon detector can illustrate the so-called quantum Zeno effect, an element of interaction-free measurements.

other particles in the atomic realm—says otherwise. Interaction-free measurements can indeed be achieved by quantum mechanics and clever experimental designs. If Perseus had been armed with a knowledge of quantum physics, he could have devised a way to "see" Medusa without any light actually striking the Gorgon and entering his eye. He could have looked without looking.

Such quantum prestidigitation offers many ideas for building detection devices that could have use in the real world. Perhaps even more interesting are the mind-boggling philosophical implications. Those applications and implications are best understood at the level of thought experiments: streamlined analyses that contain all the essential features of real experiments but without the practical complications.

So, as a thought experiment, consider a variation of a shell game, which employs two shells and a pebble hidden under one of them. The pebble, however, is special: it will turn to dust if exposed to any light. The player attempts to determine where the hidden pebble is but without exposing it to light or disturbing it in any way. If the pebble turns to dust, the player loses the game.

Initially, this task may seem impossible, but we quickly see that as long as the player is willing to be successful half the time, then an easy strategy is to lift the shell he hopes does not contain the pebble. If he is right, then he knows the pebble lies under the other shell, even though he has not seen it. Winning with this strategy, of course, amounts to nothing more than a lucky guess.

Next, we take our modification one step further, seemingly simplifying the game but in actuality making it impossible for a player limited to the realm of classical physics to win. We have only one shell, and a random chance that a pebble may or may not be under it. The player's goal is to say if a pebble is present, again without exposing it to light.

Assume there is a pebble under the shell. If the player does not look under the shell, then he gains no information. If he looks, then he knows the pebble was there, except that he has necessarily exposed it to light and so finds only a pile of dust. The player may try to dim the light so that there is very little chance of it hitting the pebble. For the player to see the pebble, however, at least one photon must have hit it, by definition, implying that he has lost.

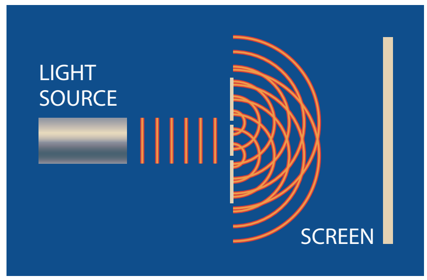
Elitzur, Vaidman and the Bomb

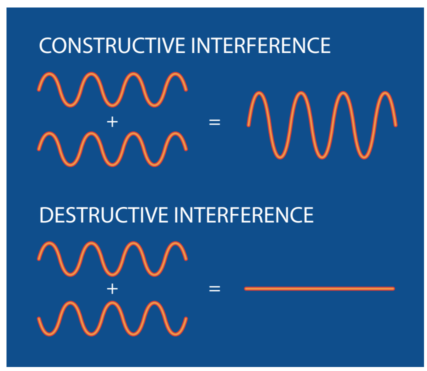
To make the game more dramatic, Avshalom C. Elitzur and Lev Vaidman, two physicists at Tel Aviv University, considered the pebble to be a "superbomb" that would explode if just a single photon hit it. The problem then became: determine if a pebble bomb sits under a shell, but don't set it off.

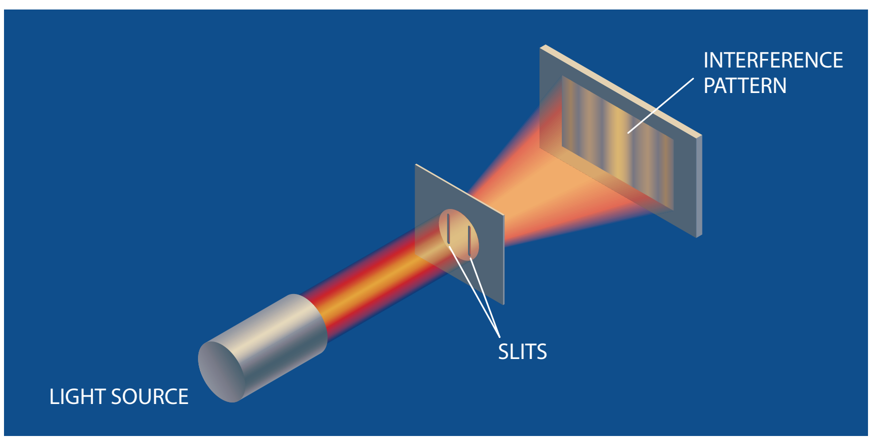
Elitzur and Vaidman were the first researchers to offer any solution to the problem. Their answer works, at best, half the time. Nevertheless, it was essential for demonstrating any hope at all of winning the game.

Their method exploits the fundamental nature of light. We have already mentioned that light consists of photons, calling to mind a particlelike quality. But light can display distinctly wavelike characteristics—notably a phenomenon called interference. Interference is the way two waves add up with each other. For example, in the well-known double-slit experiment, light is directed through two slits, one above the other, to a faraway screen. The screen then displays bright and dark fringes [*see illustration at right*]. The bright fringes correspond to places where the crests and troughs of the light waves from one slit add constructively to the crests and troughs of waves from the other slit. The dark bands correspond to destructive interference, where the crests from one slit cancel the troughs from the other. Another way of expressing this concept is to say that the bright fringes correspond to areas on the screen that have a high

INTERFERENCE occurs when a laser is shone through two slits, which generate concentric light waves that interfere with each other (*top*).The waves can add constructively or destructively (*middle*), yielding the characteristic interference pattern of bright and dark bands (*bottom*).







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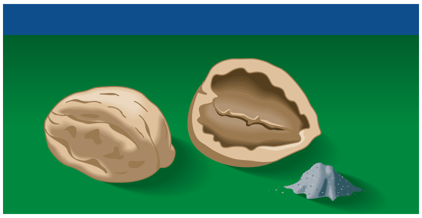

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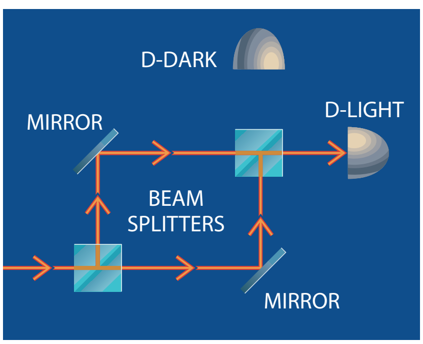
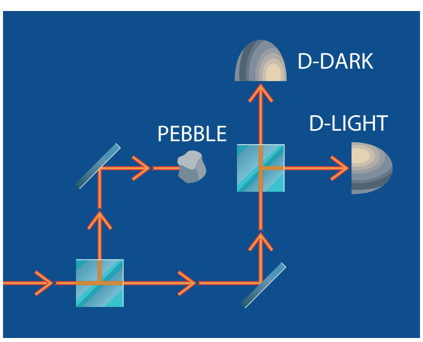
PHYSICIST'S SHELL GAME is a thought experiment that illustrates the potential of interaction-free measurements. A special pebble may be under a shell; if any light touches the pebble, it turns to dust. How can one determine which shell hides the pebble?

ELITZUR-VAIDMAN EXPERIMENT gives a photon a choice of two paths to follow. The optical elements are arranged (*top*) so that photons always go to detector D-light (corresponding to constructive interference) but never to D-dark (corresponding to destructive interference). The presence of a pebble in one path, however, occasionally sends a photon to D-dark (*bottom*), indicating that an interaction-free measurement has occurred.





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probability of photon hits, and the dark fringes to a low probability of hits.

According to the rules of quantum mechanics, interference occurs whenever there is more than one possible way for a given outcome to happen, and the ways are not distinguishable by any means (this is a more general definition of interference than is often given in textbooks). In the double-slit experiment, light can reach the screen in two possible ways (from the upper or the lower slit), and no effort is made to determine which photons pass through which slit. If we somehow could determine which slit a photon passed through, there would be no interference, and the photon could end up anywhere on the screen. As a result, no fringe pattern would emerge. Simply put, without two indistinguishable paths, interference cannot occur.

As the initial setup for their hypothetical measuring system, Elitzur and Vaidman start with an interferometer—a device consisting of two mirrors and two beam splitters. Light entering the interferometer hits a beam splitter, which sends the light along two optical paths: an upper and a lower one. The paths recombine at the second beam splitter, which sends the light to one of two photon detectors [*see illustration at left*]. Thus, the interferometer gives each photon two possible paths between the light source and a detector.

If the lengths of both paths through the interferometer are adjusted to be exactly equal, the setup effectively becomes the double-slit experiment. The main difference is that the photon detectors take the place of the screen that shows bright and dark fringes. One detector is positioned so that it will detect only the equivalent of the bright fringes of an interference pattern (call that detector D-light). The other one records the dark fringes—in other words, no photon ever reaches it (call that detector D-dark).

Pebble in the Path

What happens if a pebble is placed into one of the paths, say, the upper one? Assuming that the first beam splitter acts randomly, then with 50 percent likelihood, the photon takes the upper path, hits the pebble (or explodes the superbomb) and never gets to the second beam splitter.

If the photon takes the lower path, it does not hit the pebble. Moreover, interference no longer occurs at the second beam splitter, for the photon has only one way to reach it. Therefore, the photon makes another random choice at the second beam splitter. It may be reflected and hit detector D-light; this outcome gives no information, because it would have happened anyway if the pebble had not been there. But the photon may also go to detector D-dark. If that occurs, we know with certainty that there was an object in one path of the interferometer, for if there were not, detector D-dark could not have fired. And because we sent only a single photon, and it showed up at D-dark, it could not have touched the pebble. Somehow we have managed to make an interaction-free measurement—we have determined the presence of the pebble without interacting with it.

Although the scheme works only some of the time, we emphasize here that when the scheme works, it works completely. The underlying quantum-mechanical magic in this feat is that everything, including light, has a dual nature—both particle and wave. When the interferometer is empty, the light behaves as a wave. It can reach the detectors along both paths simultaneously, which leads to interference. When the pebble is in place, the light behaves as an indivisible particle and follows only one of the paths. The mere presence of the pebble removes the possibility of interference, even though the photon need not have interacted with it.

To demonstrate Elitzur and Vaidman's idea, we and Thomas Herzog, now at the University of Geneva, performed a real version of their thought experiment two years ago and thus demonstrated that interaction-free devices can be built. The source of single photons was a special nonlinear optical crystal. When ultraviolet photons from a laser were directed through the crystal, sometimes they were "down-converted" into two daughter photons of lower energy that traveled off at about 30 degrees from each other. By detecting one of these photons, we were absolutely certain of the existence of its sister, which we then directed into our experiment.

That photon went into an interferometer (for simplicity, we used a slightly different type of interferometer than the one Elitzur and Vaidman proposed). The mirrors and beam splitter were aligned so that nearly all the photons left by the same way they came in (the analogue of going to detector D-light in the Elitzur-Vaidman example or, in the double-slit experiment, of going to a bright fringe). In the absence of the pebble, the chance of a photon going to detector D-dark was very small because of destructive interference (the analogue of the dark fringes in the double-slit experiment) [*see illustration at right*].

But introducing a pebble into one of the pathways changed the odds. The pebble was a small mirror that directed the light path to another detector (D-pebble). We then found that about half of the time, D-pebble registered the photon, whereas about one fourth of the time D-dark did (the rest of the time the photon left the interferometer the same way it came in, giving no information). The firing of D-dark was the interaction-free detection of the pebble.

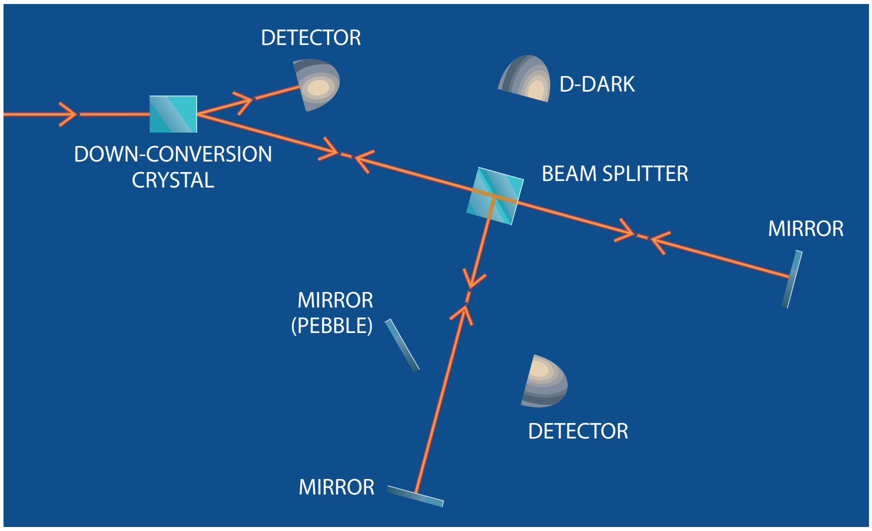
In a simple extension of the scheme, we reduced the reflectivity of the beam splitter, which lessened the chance that the photons would be reflected onto the path containing the mirror to D-pebble. What we found, in agreement with theoretical prediction, was that the probabilities of the photons going to D-pebble and going to D-dark became more and more equal. That is, by using a barely reflective beam splitter, up to half the measurements in the Elitzur-Vaidman scheme can be made interaction-free (instances in which the photons leave the interferometer the same way they came in are not counted as measurements).

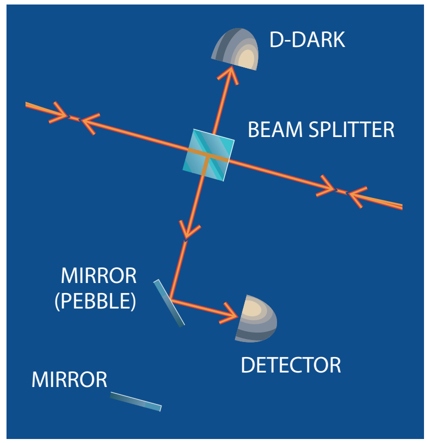
The Quantum Zeno Effect

The question immediately arose: Is 50 percent the best we can do? Considerable, often heated, argument ensued among us, for no design change that would improve the odds was evident. In January 1994, however, Mark A. Kasevich of Stanford University came to visit us at Innsbruck for a month, and during this stay he put us on to a solution that, if realized, makes it possible to detect objects in an interaction-free way almost every time. It was not the first instance, and hopefully not the last, in which quantum optimism triumphed over quantum pessimism.

The new technique is more or less an application of another strange quantum phenomenon, first discussed in detail in 1977 by Baidyanath Misra, now at the University of Brussels, and E. C. George Sudarshan of the University of Texas at Austin. Basically, a quantum system can be trapped in its initial state, even though it would evolve to some other state if left on its own. The possibility arises because of the unusual effect that measurements can have on quantum systems. The phenomenon is called the quantum Zeno effect, because it resembles the famous paradox raised by the Greek philosopher Zeno, who denied the possibility of motion to an arrow in flight because it appears "frozen" at each instant of its flight. It is also known as the watched-pot effect, a reference to the aphorism about boiling water. We all know that the mere act of watching the pot should not (and does not) have any effect on the time it takes to boil the water. In quantum mechanics, however, such an effect actually exists—the measurement affects the outcome (the principle is called the projection postulate).

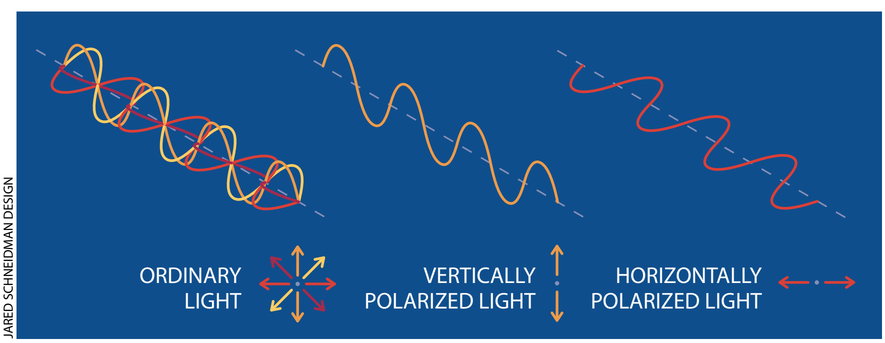
Kasevich essentially reinvented the simplest example of this effect, which was first devised in 1980 by Asher Peres of the Technion-Israel Institute of Technology. The example exploits yet another characteristic of light: polarization. Polarization is the direction in which light waves oscillate—up and down for vertically polarized light, side to side for horizontally polarized light. These oscillations are at right angles to the light's direction of propagation. Light from the sun and other typical sources generally vibrates in all directions, but

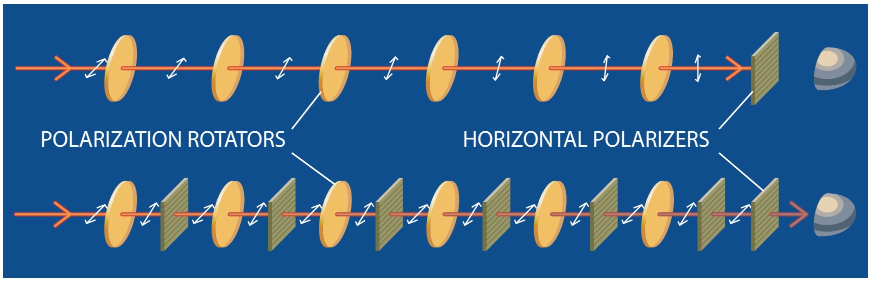




DEMONSTRATION of the Elitzur-Vaidman scheme uses light from a down-conversion crystal, which enters a beam splitter, bounces off two mirrors and interferes with itself back at the beam splitter (*top*). No light reaches D-dark (corresponding to destructive interference; constructive interference is in the direction from which the photon first came). If a mirror "pebble" is inserted into a light path, no interference occurs at the beam splitter; D-dark sometimes receives photons (*bottom*).

POLARIZATION refers to the vibrations of light waves as they move through space.





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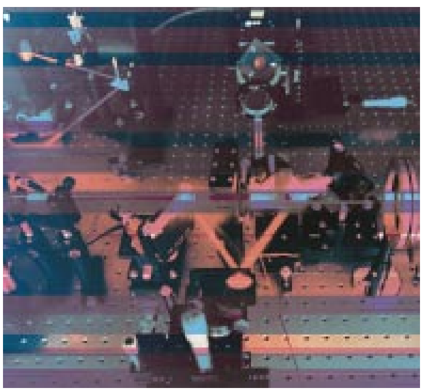
QUANTUM ZENO EFFECT can be demonstrated with devices that rotate polarization 15 degrees. After passing through six such rotators, the photon changes from a horizontal polarization to a vertical one and so is absorbed by the polarizer (*top row*). Interspersing a polarizer after each rotator, however, keeps the polarization from turning (*bottom row*).

EXPERIMENTAL REALIZATION of the quantum Zeno effect was accomplished by making the photon follow a spiral-staircase path, so that it traversed the polarization rotator six times. Inserting a polarizer next to the rotator suppressed the rotation of the photon's polarization.



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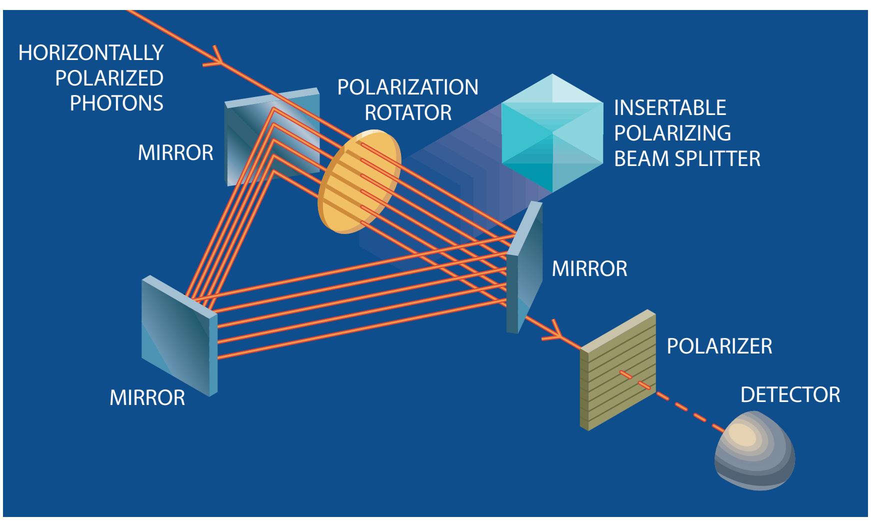

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here we are concerned mostly with vertical and horizontal polarizations.

Consider a photon directed through a series of, say, six devices that each slightly rotates the polarization of light so that a horizontally polarized photon ends up vertically polarized [*see illustration above*]. These rotators might be glass cells containing sugar water, for example. At the end of the journey through the rotators, the photon comes to a polarizer, a device that transmits photons with one kind of polarization but absorbs photons with perpendicular polarization. In this thought experiment, the polarizer transmits only horizontally polarized light to a detector.

We will start with a photon horizontally polarized, and each rotator will turn the polarization by 15 degrees. It is clear, then, that the photon will never get to the detector, for after passing through all the cells, its polarization will have turned 90 degrees (15 degrees for each of the six rotators) so that it becomes vertical. The polarizer absorbs the photon. This stepwise rotation of the polarization is the quantum evolution that we wish to inhibit.

Interspersing a horizontal polarizer between each polarization rotator does the trick. Here's why: After the first rotator, the light is not too much turned from the horizontal. This means that the chance that the photon is absorbed in the first horizontal polarizer is quite small, only 6.7 percent. (Mathematically, it is given by the square of the sine of the turning angle.)

If the photon is not absorbed in the first polarizer, it is again in a state of horizontal polarization—it must be, because that is the only possible state for light that has passed a horizontal polarizer. At the second rotator, the polarization is once again turned 15 degrees from the horizontal, and at the second polarizer, it has the same small chance of being absorbed; otherwise, it is again transmitted in a state of horizontal polarization. The process repeats until the photon comes to the final polarizer.

An incident photon has a two-thirds chance of being transmitted through all six inserted polarizers and making it to the detector; the probability is given by the relation $(\cos^2(15\text{ degrees}))^6$. Yet as we increase the number of stages, decreasing the polarization-rotation angle at each stage accordingly (that is, 90 degrees divided by the number of stages), the probability of transmitting the photon increases. For 20 stages, the probability that the photon reaches the detector is nearly 90 percent. If we could make a system with 2,500 stages, the probability of the photon being absorbed by one of the polarizers would be just one in 1,000. And if it were possible to have an infinite number of stages, the photon would always get through. Thus, we would have completely inhibited the evolution of the rotation.

To realize the quantum Zeno effect, we used the same nonlinear crystal as before to prepare a single photon. Instead of using six rotators and six polarizers, we used just one of each; to achieve the same effect, we forced the photon through them six times, employing three mirrors as a kind of spiral staircase [*see illustration at left*]. In the absence of the polarizer, the photon exiting the staircase is always found to be vertically polarized. When the polarizer is present, we found that the photon was horizontally polarized (unless the polarizer blocked it). These cases occurred roughly two thirds of the time for our six-cycle experiment, as expected from our thought-experiment analysis.

Next we set out to make an interaction-free measurement—that is, to detect an opaque object without any photons hitting it—in a highly efficient manner. We devised a system that was somewhat of a hybrid between the Zeno example and the original Elitzur-Vaidman method. A horizontally polarized photon is let into the system and makes a few cycles (say, six again) before leaving. (For this purpose, one needs a mirror that can be "switched" on and off very quickly; fortunately, such mirrors, which are actually switchable interference devices, have already been developed for pulsed lasers.) At one end of the system is a polarization rotator, which turns the photon's polarization by 15 degrees in each cycle. The other end contains a polarization interferometer. It consists of a polarizing beam splitter and two equal-length interferometer paths with mirrors at the ends [*see illustration at right*].

At the polarizing beam splitter, all horizontally polarized light is transmitted, and all vertically polarized light is reflected; in essence, the transmission and reflection choices are analogous to the two paths in the double-slit experiment. In the absence of an object in the polarization interferometer, light is split at the beam splitter according to its polarization, reflects off the mirrors in each path and is recombined by the beam splitter. As a result, the photon is in exactly the same state as before it entered the interferometer (that is, with a polarization turned 15 degrees toward the vertical). So, after six cycles, the polarization ends up rotated to vertical.

The situation changes when an opaque object is placed in the vertical polarization path of the interferometer. This situation is analogous to having the six polarizers inserted in the quantum Zeno effect experiment. So in the first cycle, the chance that the photon—the polarization of which has been turned only 15 degrees from horizontal—enters the vertical-polarization path (and is then absorbed by the object) is very small (6.7 percent, as in the Zeno thought experiment). If this absorption does not happen, the photon must have entered the horizontal path instead, and its polarization is reset to be purely horizontal.

Just as in the Zeno example, the whole process repeats at each cycle, until finally, after six cycles, the bottom mirror is switched off, and the photon leaves the system. Measuring the photon's polarization, we find it still to be horizontal, implying that a blocker must reside in the interferometer. Otherwise, the photon would have been vertically polarized when it left. And by using more cycles, we can make the probability that the photon is absorbed by the object as small as we like. Preliminary results from new experiments at Los Alamos National Laboratory have demonstrated that up to 70 percent of measurements could be interaction-free. We soon hope to increase that figure to 85 percent.

Applying Quantum Magic

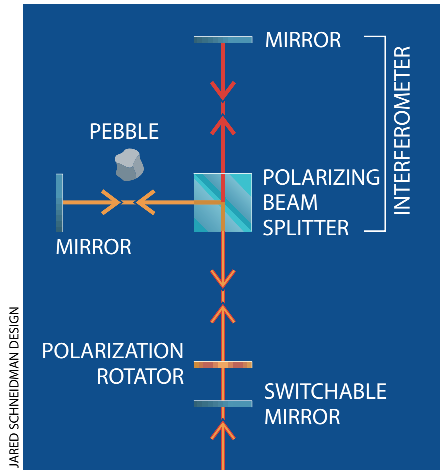
What good is all this quantum conjuring? We feel that the situation resembles that of the early years of the laser, when scientists knew it to be an ideal solution to many unknown problems. The new method of interaction-free measurement could be used, for instance, as a rather unusual means of photography, in which an object is imaged without being exposed to light.

The "photography" process would work in the following way: Instead of sending in one photon, we would send in many photons, one per pixel, and perform interaction-free measurements with them. In those regions where the object did not block the light path of the interferometer, the horizontal polarization of the photons would undergo the expected stepwise rotation to vertical. In those regions where the object blocked the light path, a few of the photons would be absorbed; the rest would have their polarizations trapped in the horizontal state. Finally, we would take a picture of the photons through a polarizing filter after they had made the requisite number of cycles.

If the filter were horizontally aligned, we would obtain an image of the object; if vertically aligned, we would obtain the negative. In any case, the picture is made by photons that have never touched the object. These techniques can also work with a semitransparent object and may possibly be generalized to find out an object's color (although these goals would be more difficult).

A variation of such imaging could someday conceivably prove valuable in medicine—for instance, as a means to image living cells. Imagine being able to x-ray someone without exposing them to many penetrating x-rays. Such imaging would therefore pose less risk to patients than standard x-rays. (Practically speaking, such x-ray photography is unlikely to be realized, considering the difficulty of obtaining optical elements for this wavelength of light.)

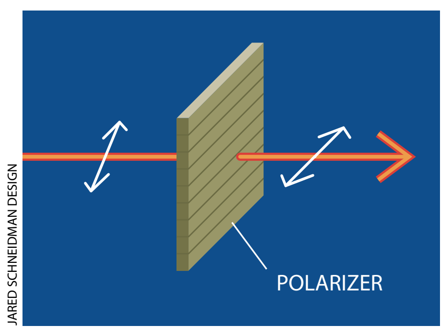
A candidate for more immediate application is the imaging of the clouds of

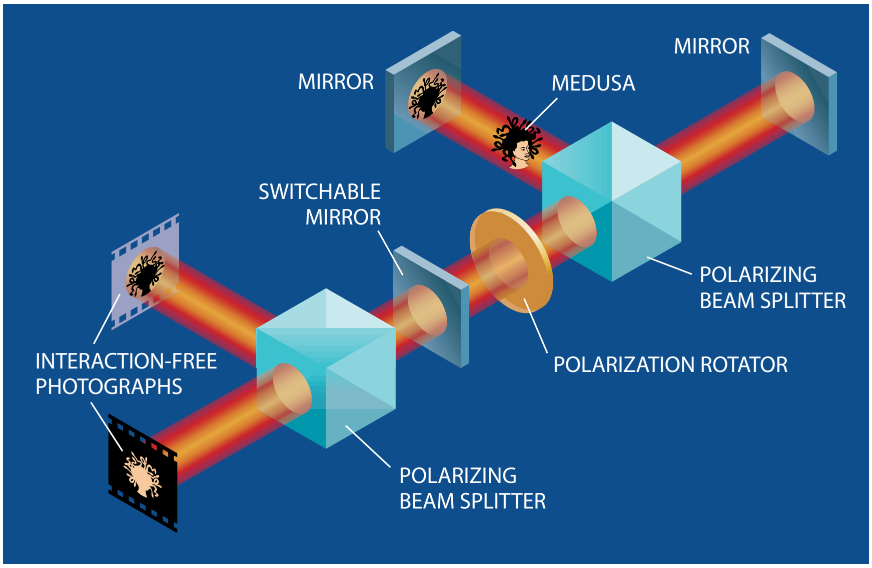


EFFICIENT MEASUREMENTS that are interaction-free combine the setups of the quantum Zeno effect and the Elitzur-Vaidman scheme. The photon enters below the switchable mirror and follows the optical paths six times before being allowed to exit through the mirror. Its final polarization will still be horizontal if there is a pebble in one light path; otherwise, it will have rotated to a vertical polarization.

The Projection Postulate

The postulate states that for any measurement made on a quantum system only certain answers are possible. Moreover, after the measurement, the quantum system is in a state determined by the obtained results. So a photon that has passed through a horizontal polarizer is necessarily horizontally polarized, even if it were originally polarized at a nearly vertical angle (the polarizer eliminates the vertical component of the polarization). The probability of transmission in this case, though, would be low.





PHOTOGRAPHY can also be done with interaction-free techniques. In this way, the object—a "Medusa" that must not be viewed directly—will absorb very few photons.

ultracold atoms recently produced in various laboratories. The coldest of these exhibit Bose-Einstein condensation, a new type of quantum state in which many atoms act collectively as one entity. In such a cloud every atom is so cold—that is, moving so slowly—that a single photon can knock an atom out of the cloud. Initially, no way existed to get an image of the condensate without destroying the cloud. Interaction-free measurement methods might be one way to image such a collection of atoms.

Besides imaging quantum objects, interaction-free procedures could also make certain kinds of them. Namely, the techniques could extend the creation of "Schrödinger's cat," a much loved theoretical entity in quantum mechanics. The quantum feline is prepared so that it exists in two states at once: it is both alive and dead at the same time—a superposition of two states. Earlier this year workers at the National Institute of Standards and Technology managed to create a preliminary kind of Schrödinger's cat—a "kitten"—with a beryllium ion. They used a combination of lasers and electromagnetic fields to make the ion exist simultaneously in two places spaced 83 nanometers apart—a vast distance on the quantum scale.

If such an ion were interrogated with the interaction-free methods, the interrogating photon would also be placed in a superposition. It could end up being horizontally and vertically polarized at the same time. In fact, the kind of experimental setup discussed above should be able to place a group of, say, 20 photons in the same superposition. Every photon would "know" that it has the same polarization as all the others, but none would know its own polarization. They would remain in this superposition until a measurement revealed them to be all horizontally polarized or all vertically polarized. The sizable bunch of photons stuck in this peculiar condition would show that quantum effects can be manifested at the macroscopic scale.

Lying beyond the scope of everyday experience, the notion of interaction-free measurements seems weird, if not downright nonsensical. Perhaps it would seem less strange if one kept in mind that quantum mechanics operates in the realm of potentialities. It is because there *could* have been an interaction that we can prevent one from occurring.

If that does not help, take comfort in the fact that, over the years, even physicists have had a hard time accepting the strangeness of the quantum world. The underlying keys to these quantum feats of magic—the complementary, wave-and-particle aspect of light and the nature of quantum measurements—have been known since 1930. Only recently have physicists started to apply these ideas to uncover new phenomena in quantum information processing, including the ability to see in the dark. SA

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PAUL KWIAT, HARALD WEINFURTER and ANTON ZEILINGER freely interacted with one another at the University of Innsbruck. Kwiat, now a J. R. Oppenheimer Fellow at Los Alamos National Laboratory, earned his Ph.D. from the University of California, Berkeley. He is a serious student of aikido and is trying to become a tolerable flautist. Weinfurter received his Ph.D. from the Technical University of Vienna and held a postdoctoral position at the Hahn-Meitner Institute in Berlin. He currently enjoys all the benefits and comforts of a fellowship from the Austrian Academy of Science as well as the relaxing lifestyle in Innsbruck and its surrounds. A member of the Austrian Academy of Sciences, Zeilinger earned his doctorate at the University of Vienna and has held numerous appointments worldwide. In his little free time, he plays the double bass and collects antique maps, particularly of the Austro-Hungarian empire.

Further Reading

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Discussions on experiments for interaction-free measurements can be found on the World Wide Web at http://info.uibk.ac.at/c/c7/c704/qo/photon/#Inter and at http://p23.lanl. gov/Quantum/kwiat/ifm-folder/ifmtext.htm