Also by Amit Goswami

The Concepts of Physics
Quantum Mechanics

With Maggie Goswami

The Cosmic Dancers

THE SELF-AWARE UNIVERSE

HOW CONSCIOUSNESS CREATES THE MATERIAL WORLD

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within the framework of monistic idealism. The result is an idealist science that integrates spirit and matter.

The idea that consciousness collapses the quantum wave was originally proposed by the mathematician John von Neumann in the 1930s. What took us so long to take this idea seriously? Perhaps a brief discussion of how my own clarity on this issue developed will help.

One of the difficulties I had with von Neumann's proposal had to do with experimental data. When we look, we seem to be always conscious. Then the question of consciousness collapsing the quantum waves seems purely academic. Could one ever find a situation where one is looking, but is not conscious? Notice how paradoxical this sounds.

In 1983, I was invited to a ten-week-long seminar on consciousness at the psychology department at the University of Oregon. I was particularly flattered that these erudite psychologists patiently listened to six full hours of talks that I gave on the quantum ideas. The real reward came, however, when one of the graduate students of psychologist Michael Posner's group reported some cognitive data collected by a fellow named Tony Marcel. Some of the data concerned "unconscious seeing": exactly what I was looking for.

With heart palpitating, I listened to the data and relaxed only when I realized that the data are completely in agreement with consciousness collapsing the quantum state of the brain-mind when we see consciously (see chapter 7). In unconscious seeing, there is no collapse, and that really made a lot of experimental difference. Soon I realized also how to resolve the slight paradox that the distinction of conscious and unconscious perception creates. The trick is to distinguish between consciousness and awareness.

Chapter 5

OBJECTS IN TWO PLACES AT ONCE AND EFFECTS THAT PRECEDE THEIR CAUSES

THE FUNDAMENTAL TENETS of material realism simply do not hold up. In place of causal determinism, locality, strong objectivity, and epiphenomenalism, quantum mechanics offers probability and uncertainty, wave-particle complementarity, nonlocality, and mixing of subjects and objects.

About the probability interpretation of quantum mechanics, which breeds uncertainty and complementarity, Einstein used to say that God does not play dice. To see what he meant imagine that you are doing an experiment with a radioactive sample that, of course, obeys probabilistic quantum laws of decay. Your job is to measure the time it takes for ten radioactive events—ten clicks of your Geiger counter. Suppose further that it takes on the average half an hour for the ten cases of radioactive decay to occur. Behind that average lurks probability. Some runs could take thirty-two minutes, other runs twenty-five minutes, and so on. To complicate things, you have a bus to catch to meet your fiance, who absolutely hates to be kept waiting. And guess what? Your last run takes forty minutes because a single atom, at random, will not decay like the average ones did. So you miss your bus, your fiance breaks up with you, and your life is ruined.[1] This may be a somewhat silly, concocted example of what happens in a world whose God plays dice, but it does make the point. Probabilistic events can be depended on only on the average.

The randomness of atomic events—the diciness of fate, as it were—is abhorrent to a determinist. The determinist thinks about probability in the way in which we think of it in classical physics and in everyday life: It is a characteristic of large ensembles of objects—ensembles so large and intricate that we cannot, as a practical matter, predict them, though such prediction is possible in principle. To the determinist, probability is simply a convenience of thought; the physical laws that guide the motions of individual objects are completely determined and therefore completely predictable. It was Einstein's belief that the quantum mechanical universe is also this way: There are hidden variables behind the quantum uncertainties. The probabilities of quantum mechanics are simply matters of convenience. If such were the case, quantum mechanics would have to be a theory of ensembles. Indeed, if we do not apply the probability wave description to a single quantum object, then we do not get into the paradoxes that excite us—wave-particle complementarity and the inseparability of the quantum object from considerations of its observation.

Unfortunately, things are not that simple. Considering a couple of quantum-mechanical experiments will show how hard it is to rationalize away the paradoxes of quantum physics.

THE DOUBLE-SLIT EXPERIMENT

We can never see the wave aspect of a single wavicle. Whenever we look, all we see is the localized particle. Should we, therefore, assume that the solution is transcendent metaphysics? Or should we abandon the idea that there is a wave aspect of a single wavicle? Perhaps the waves that appear in quantum physics are a characteristic only of groups or ensembles of objects.

To determine whether this is so, we can analyze an experiment commonly used to study wave phenomena: the double-slit experiment. In the setup for this experiment, a beam of electrons passes through a screen that has two narrow slits in it (fig. 14). Since electrons are waves, the beam is split into two sets of waves by the two-slitted screen. These waves then interfere with one another, and the result of the interference shows on a fluorescent screen.

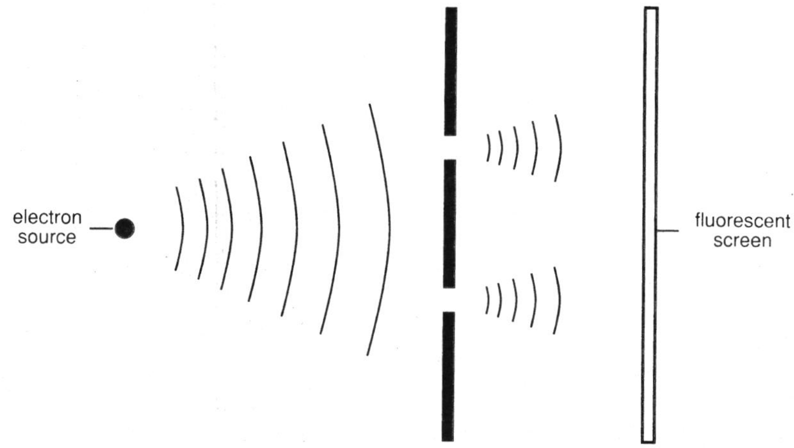

Figure 14. The double-slit experiment for electrons.

Simple enough? Let me review the phenomenon of wave interference. For an easy demonstration, if you are not familiar with the interference phenomenon, stand in a bathtub filled with water and make two water-wave trains by rhythmically marching in place. The waves will make an interference pattern (fig. 15a). At some points they will reinforce each other (fig. 15b); at other points they will cause mutual destruction (fig. 15c). Hence, the pattern.

Similarly, there are places on the fluorescent screen where the electron waves from the two slits arrive in phase, matching their dance steps. At these places their amplitudes add, and the total wave is reinforced. In between these bright spots there are places where the two waves arrive out of phase and cancel each other out. The result of this constructive and destructive interference, then, shows on the fluorescent screen as a pattern of alternating bright and dark fringes: an interference pattern (fig. 16). Importantly, the spacing of the fringes enables us to measure the wavelength of the waves.

Remember, though, that the electron waves are probability waves. Thus we must say that it is the probability of an electron arriving at the light areas that is high, and the probability of an electron arriving at the dark areas that is low. We must not get carried away and conclude from the interference pattern that the electron waves are classical waves, because the electrons do arrive at the fluorescent screen in a very particlelike way: one localized flash per electron. It

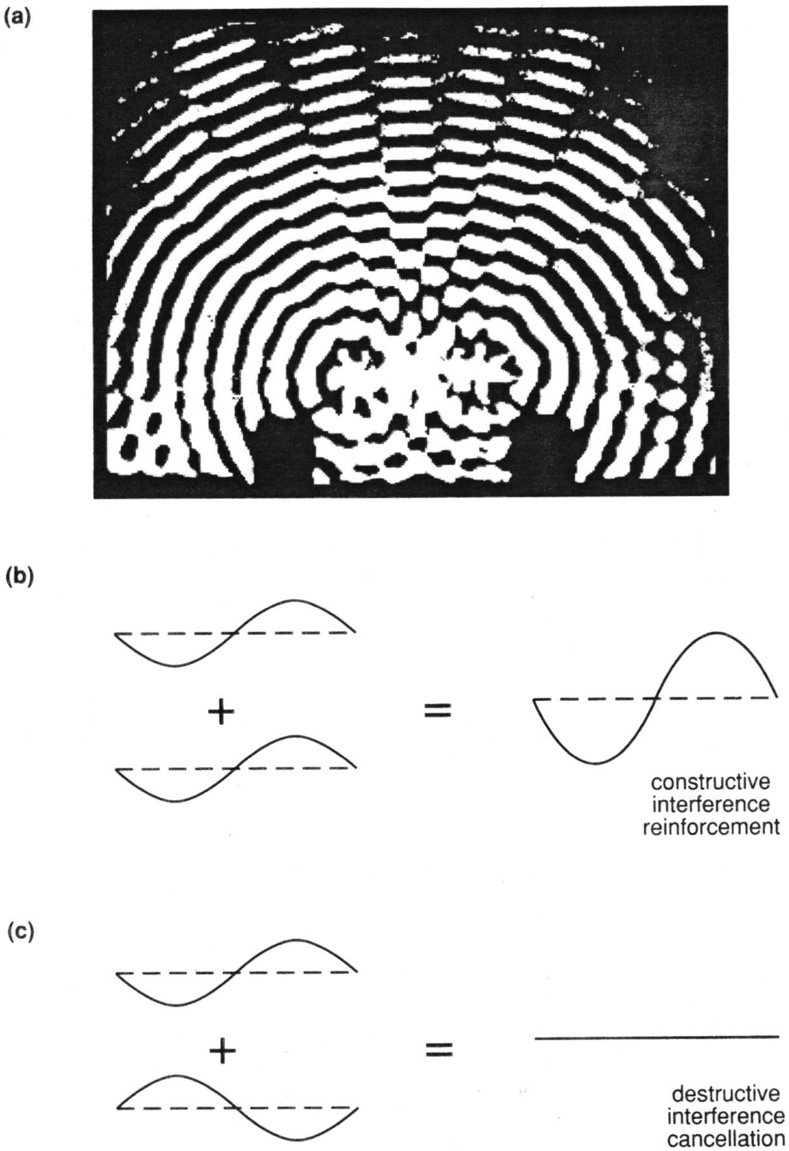

Figure 15. (a) When water waves interfere, they make an interesting pattern of reinforcements and cancellations. (b) When waves arrive in phase, they reinforce each other. (c) Waves out of phase: result—cancellation.

Figure 16. The interference pattern of flashes on screen.

is the totality of spots made by a large number of electrons that looks like the wave interference pattern.

Suppose we take an intellectual risk and make the electron beam very weak—so weak that at any one moment only one electron arrives at the slits. Do we still get an interference pattern? Quantum mechanics unambiguously says yes. We cannot, you may object, get interference without a split beam. Doesn't it take two waves to interfere? Can a single electron split, pass through both slits, and interfere with itself? Yes, it can. Quantum mechanics says yes to all these questions. As Paul Dirac, one of the pioneers of the new physics, put it: "Each photon [or here, electron] interferes only with itself." The proof that quantum mechanics offers for this preposterous proposition is mathematical, but this one proposition is responsible for all the miraculous magic that quantum systems are capable of and that has been verified by myriad experiments and technologies.

Try to imagine that an electron is passing 50 percent through one slit and 50 percent through the other slit. It is easy to get exasperated and to disbelieve this strange consequence of quantum mathematics. Does the electron really pass through both slits at the same time? Why should we take that for granted? We can find out by looking. We can focus a flashlight (metaphorically speaking) on a slit to see which hole the electron is really passing through.

So we turn the light on, and as we see an electron passing through a particular slit, we look to see where the flash appears on the fluorescent screen (fig. 17). What we find is that every time an electron goes through a slit, its flash appears just behind the slit it passes through. The interference pattern has disappeared.

What is happening in this experiment can be understood, in the first place, as a play of the uncertainty principle. As soon as we locate the electron and determine which slit it passes through, we lose the information about the electron's momentum. Electrons are very delicate; the collision with the photon that we are using to observe it affects it so that its momentum changes by an unpredictable amount.

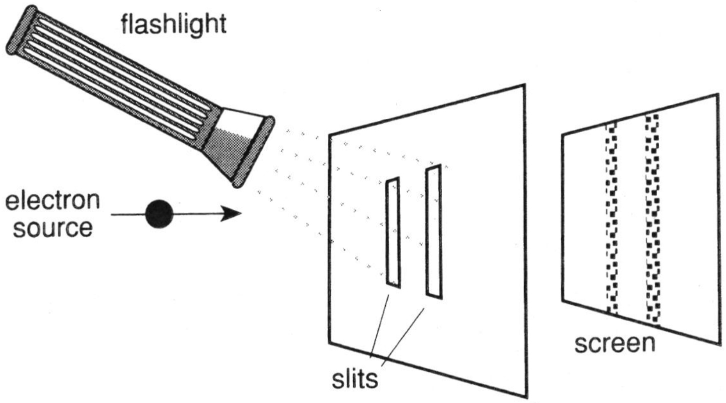

Figure 17. When we try to identify which slit the electron passes through by focusing a flashlight on the slits, the electron shows its particle nature. There are only two fringes—exactly what we would expect if the electrons were miniature baseballs.

The electron's momentum and the wavelength are related: This is de Broglie's great discovery that quantum mathematics incorporates. Thus losing the information about the electron's momentum is the same as losing information about its wavelength. If there were interference fringes, we would be able to measure the wavelength from their spacing. The uncertainty principle says that as soon as we determine which slit the electron is passing through, the process of looking destroys the interference pattern.

You must realize that the measurements on the electron's position and momentum are really complementary, mutually exclusive processes. We can concentrate on the momentum and measure the wavelength—and thus the momentum—of the electron from the interference pattern, but then we cannot tell which slit the electron goes through. Or we can concentrate on the position and lose the interference pattern, the information about the wavelength and momentum.

There is a second, even more subtle way to understand and reconcile all this—the way of the complementarity principle. Depending on which apparatus we choose, we see the particle aspect (for example, with a flashlight) or the wave aspect (no flashlight).

To understand the complementarity principle as saying that quantum objects are both wave and particle but that we can see only one attribute with a particular experimental arrangement is cer-

tainly correct, but our experience is teaching us some subtleties. For example, we must also say that the electron is neither a wave (because the wave aspect never manifests for a single electron) nor a particle (because it appears on the screen at places forbidden for particles). Then, if we are cautious in our logic, we must also say that the photon is neither not-wave nor not-particle, just so there is no misunderstanding about our use of the words *wave* and *particle*. This is much like the logic of the idealist philosopher Nagarjuna in the first century A.D., the most astute logician of the *Mahayana* Buddhist tradition.[2] Eastern philosophers communicate their understanding of ultimate reality as *neti, neti* (not this, not that). Nagarjuna formulated this teaching into four negations:

It does not exist.
It does not not exist.
It does not both exist and not exist.
Nor does it neither exist nor not exist.

To understand complementarity more clearly, suppose we go back to the previous experiment, this time using weak batteries to make the flashlight that we shine on the electrons somewhat dimmer. When we repeat the experiment of figure 17 with dimmer and dimmer flashlights, we find that some of the interference pattern begins to reappear, becoming more and more prominent as we make the flashlight dimmer and dimmer (fig. 18). When the flashlight is turned off completely, the full interference pattern comes back.

As the flashlight dims, the number of photons scattering off the electrons decreases, so some of the electrons entirely escape being "seen" by the light. Those electrons that are seen appear behind slit 1 or slit 2, just where we would expect them. Each of the unseen electrons splits and interferes with itself to make the wave-interference pattern on the screen when enough electrons have arrived there. In the limit of strong light, only the particle nature of the electrons is seen; in the limit of no light, only the wave nature is

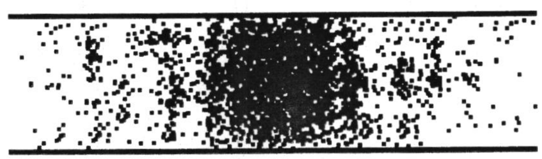

Figure 18. With a dimmer flashlight, some of the interference pattern returns.

seen. In the case of various intermediate situations of dim light, both aspects show up to a similarly intermediate degree: that is, here we are seeing electrons (though never the same electron) as simultaneously wave and particle. Thus the wave nature of a wavicle is not a property of the whole ensemble but must hold for each individual wavicle whenever we are not looking. That must mean that the wave aspect of a single quantum object is transcendent, since we never see it manifest.

A series of pictures helps explain what is going on (fig. 19). In the picture on the lower left, we see the letter W only; this corresponds to using a strong flashlight, which shows only the particle nature of the electrons. Then as we scan the ascending pictures, we begin to see the eagle—just as when we begin to make the light dimmer,

Figure 19. The W-Eagle sequence.

some electrons escape observation (and localization), and we sta seeing their wave nature. Finally, in the last figure, upper right, onl the eagle can be seen; the flashlight has been turned off, and th electrons are all waves now.

Niels Bohr once said: "Those who are not shocked when they firs come across quantum theory cannot possibly have understood it. That shock yields to understanding as we begin to comprehend th play of the complementarity principle. The formal cadence of pre dictive science that holds for either wave or particle is transforme into a creative dance of a transcendent wavicle. When we localiz the electron by finding out which slit it goes through, we reveal it particle aspect. When we do not localize the electron, ignorin which slit it goes through, we reveal its wave aspect. In the latte case, the electron passes through both slits.

THE DELAYED-CHOICE EXPERIMENT

Let us be clear about this unique characteristic of the complemen tarity principle: What attribute the quantum wavicle reveals de pends on how we choose to observe it. Nowhere is the importance o conscious choice in the shaping of manifest reality better demon strated than in the delayed-choice experiment suggested by physi cist John Wheeler.

Figure 20 shows an apparatus in which a beam of light is split int two beams, each of equal intensity—one reflected and on transmitted—by using a half-silvered mirror M_1. These two beam are then reflected by two regular mirrors A and B to a crossing poin P on the right.

To detect the wave aspect of the wavicle, we take advantage of th phenomenon of wave interference and put a second half-silvere mirror M_2 at P (fig. 20, bottom left). The two waves created by bear splitting at M_1 are now forced by M_2 to interfere constructively o one side of P (where if we place a photon counter, the counter ticks and destructively on the other side (where a counter never ticks) Notice that when we are detecting the wave mode of the photons, w must agree that each photon splits up at M_1 and travels by bot routes A and B, otherwise how can there be interference?

So when the mirror M_1 splits the beam, each photon potentially i ready to travel both paths. If we now choose to detect the particl mode of the photon wavicles, we take away the mirror M_2 at P (t

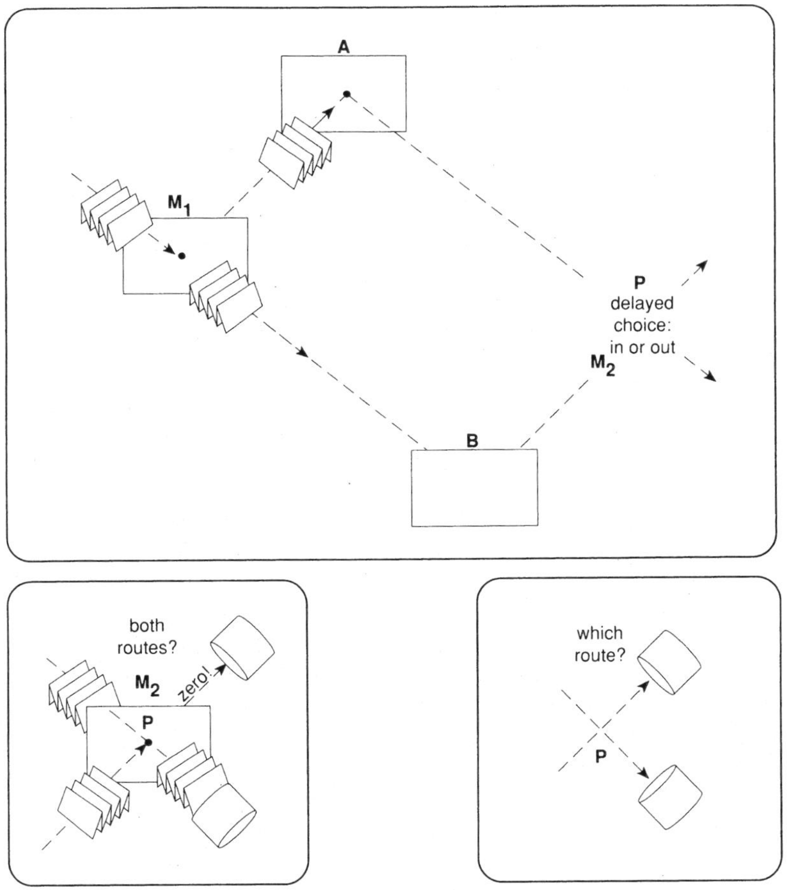

Figure 20. The delayed-choice experiment. LOWER LEFT: the arrangement for seeing the wave nature of photons. One of the detectors never detects any photons, signifying cancellation due to wave interference. The photon must have split and traveled both routes at the same time. LOWER RIGHT: the arrangement for seeing the particle nature of photons. Both detectors click, although only one at a time—signifying which route the photon takes.

prevent recombination and interference) and put counters past the point of crossing *P*, as shown in the lower right in figure 20. One or the other counter will tick, defining the localized path of a wavicle, the reflected path *A* or the transmitted path *B*, to show its particle aspect.

The subtlest aspect of the experiment is as follows: In the delayed-choice experiment, the experimenter decides at the very last moment, in the very last pico (10^{-12}) second (this has been done in the laboratory),[3] whether or not to insert the half-silvered mirror at *P*, whether or not to measure the wave aspect. In effect, this means that the photons have already traveled past the point of splitting (if you think of them as classical objects). Even so, inserting the mirror at *P* always shows the wave aspect and not inserting the mirror shows the particle aspect. Was each photon moving in one path or two? The photons seem to respond even to our delayed choice instantly and retroactively. A photon travels one path or both paths, exactly in harmony with our choice. How does it know? Is the effect of our choice preceding its cause in time? Says Wheeler: "Nature at the quantum level is not a machine that goes its inexorable way. Instead, what answer we get depends on the question we put, the experiment we arrange, the registering device we choose. We are inescapably involved in bringing about that which appears to be happening."[4]

There is no manifest photon until we see it, and thus how we see it determines its attributes. Before our observation, the photon splits into two wave packets (a packet for each path), but these packets are only packets of possibilities for the photon; there is no actuality in space-time, no decision making at M_1. Does the effect precede its cause and violate causality? It certainly does—if you think of the photon as a classical particle always manifest in space-time. The photon, however, is not a classical particle.

From the viewpoint of quantum physics, if we put a second mirror at *P* in our delayed-choice experiment, the two split-up packets in potentia combine and interfere; there is no problem. If there were a mirror at *P* and we removed it at the last-possible pico second, detecting the photon in path *A*, say, it would seem that the photon is responding to our delayed choice retroactively by traveling only in one path. In this case, therefore, the effect seems to be preceding the cause. This result does not violate causality. How so?

You must comprehend a more subtle way of looking at the second particle-aspect detection experiment, as elucidated by Heisenberg: "If now an experiment yields the result that the photon is, say, in the reflected part of the [wave] packet [path *A*], then the probability of finding the photon in the other part of the packet immediately becomes zero. The experiment in the position of the reflected packet then exerts a kind of action . . . at the distant point occupied by the transmitted packet, and one sees [that] this action is propagated with a velocity greater than light. However, it is also obvious that this kind of action can never be utilized to transmit a signal so that it [does] . . . not conflict with the postulates of the theory of relativity."[5]

This action-at-a-distance is an important aspect of the collapse of the wave packet. The technical term that we use for such action-at-a-distance is *nonlocality*—action transmitted without signals that propagate through space. Signals that propagate through space, taking a finite time because of the Einsteinian speed limit, are called *local signals.* So the collapse of the quantum wave is nonlocal.

Note that the point Heisenberg makes holds with or without delayed choice. In the quantum view, the critical point is that we choose the specific outcome that manifests; when, in time, we choose that outcome is unimportant. The wave splits whenever there are two available paths, but the split occurs only in potentia. When, later, we observe the photon in one path because we so choose (by removing the mirror at P), our collapsing the wave in one path exerts a nonlocal influence on the wave in the other path that negates the possibility of the photon being seen in that other path. Such a nonlocal influence may seem retroactive, but we are influencing only possibilities in potentia; there is no breakdown of causality because, as Heisenberg says, we cannot transmit a signal through this kind of device.

In our search for the meaning and structure of reality, we are facing the same puzzle that confronted Winnie-the-Pooh:

> 'Hallo!' said Piglet, 'what are *you* doing?'
> 'Hunting,' said Pooh.
> 'Hunting what?'
> 'Tracking something,' said Winnie-the-Pooh very mysteriously.
> 'Tracking what?' said Piglet, coming closer.
> 'That's just what I ask myself. I ask myself, What?'
> 'What do you think you'll answer?'
> 'I shall have to wait until I catch up with it,' said Winnie-the-Pooh. 'Now, look there.' He pointed to the ground in front of him. 'What do you see there?'
> 'Tracks,' said Piglet. 'Paw-marks.' He gave a little squeak of excitement. 'Oh, Pooh! Do you think it's a——a——a Woozle?'
> 'It may be,' said Pooh. 'Sometimes it is, and sometimes it isn't. You never can tell with paw-marks.'
> 'Wait a moment,' said Winnie-the-Pooh, holding up his paw. He sat down and thought, in the most thoughtful way he could think. Then he fitted his paw into one of the Tracks . . . and then he scratched his nose twice, and stood up.
> 'Yes,' said Winnie-the-Pooh. 'I see now,' said Winnie-the-Pooh. 'I have been Foolish and Deluded,' said he, 'and I am a Bear of No Brain at All.'
> 'You're the Best Bear in All the World,' said Christopher Robin soothingly.[6]

How puzzling indeed that the "woozle" tracks that the electron and other submicroscopic particles leave in our cloud chambers are, according to the new physics, merely extensions of ourselves.

The classical scientist looked at the world and saw his single vision of separateness. A couple of centuries ago, the English romantic poet William Blake wrote:

> *may God us keep*
> *From single vision and Newton's sleep.*[7]

Quantum physics is the answer to Blake's prayer. The quantum scientist who has learned the lesson of the complementarity principle knows better than to heed (apparent) separateness.

Quantum measurements interject our consciousness into the arena of the so-called objective world. There is no paradox in the delayed-choice experiment if we give up the idea that there is a fixed and independent material world even when we are not observing it. Ultimately, it boils down to what you, the observer, want to see. This reminds me of a Zen story.

Two monks were arguing about the motion of a flag in the wind. Said one: "The flag is moving." "No, the wind is moving," said the other. A third monk, who was passing by, made an observation that Wheeler would approve. "The flag is not moving. The wind is not moving. Your mind is moving."