20

Heisenberg's Uncertainty Principle and the Many Worlds Interpretation of Quantum Mechanics

July, 1981

YOU'VE dropped a coin between some cushions in a fancy old chair. You're very anxious to retrieve your coin, so you gingerly try to reach between the cushions and grab the coin. But the very act of sticking your hand in there widens the crevice and the coin slips farther in. You can see hat any more of this reaching, and your coin will be lost forever in the innards of that chair. What to do? This commonplace little drama illustrates a feeling we all know: that striving for something can have the effect of reducing that thing's availability.

A good friend is visiting from far away and before she returns home, you want to capture her infectious smile on film. But she is terribly camera-shy. The instant you bring out your camera, she freezes: spontaneity is lost, and there is no way to record that smile. The act of trying to capture this elusive phenomenon completely destroys the phenomenon.

Examples such as these are sometimes erroneously attributed to the uncertainty principle. That notorious principle of quantum mechanics was first enunciated by Werner Heisenberg in about 1927. Careless paraphrases since then, however, have eroded and obscured the true meaning of the principle in the popular mind. I would like to clarify matters a bit by discussing the genuine uncertainty principle and its phony imitators.

Let me first exhibit a typical imitation version clearly, so that you know what I am attacking. The standard pseudo-uncertainty principle states:

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The observer always interferes with the phenomenon under observation.

It tends to be cited heavily in particular domains, often where the phenomenon involves a reciprocal observer-someone who can observe back. But even in such cases, this pseudo-principle is too simplistic. It rests on a misunderstanding of how experimentation proceeds, and how science explains. The main thing to keep in mind is _that science is about classes of events, not particular instances. Science explains through abstractions that underlie a potentially unlimited number of concrete phenomena.

Consider the following example. I recently read of a woman who remarked, "Rosa always date shranks." She had meant to say, "Rosa always dated shrinks." But the tense marker somehow got shifted from the verb "date" onto the noun "shrink", which was then conjugated as if it were functioning as a verb: "dated shrinks" became "date shranks". It would be fascinating to know, exactly what was going on in the woman's brain as she made this bizarre transformation. We would like to know exactly how things went awry. Something went down the wrong track: what, and why?

But this was a one-shot phenomenon; it will probably never be repeated. We can't expect a scientific explanation of those details. Instead, we have to abstract some general phenomenon that, we think is the essential component of this particular event. We have to be able to imagine other events in the same general class. We have to be able to imagine some way to provoke them or to detect them when they happen, so that we can study the patterns. Perhaps the appropriate level of abstraction is: "grammatical errors in the speech of woman W". Or perhaps it is: "shifts of tense markers from verbs to nouns". In any case, we will have to plan a course of experimentation suitable to the way we choose to abstract this event.

In the case of the camera-shy friend, presumably her smile is a repeatable phenomenon; in missing it once, you haven't missed it forever. And with sufficient patience and ingenuity, you could set up a telephoto lens on a distant camera controlled remotely by a button you can carry in your hand. You could put the camera in an unlikely window a few dozen yards from a table where you sneakily take your friend one day, and then snap her smile without her ever suspecting it.

In the case of the coin in the cushion, with some effort you could make a special tool to retrieve it with. In fact, in any such everyday case, even those involving reciprocal observers, by investing sufficient effort and time and ingenuity-and most likely money-into a revised version, you will find you can isolate the phenomenon, you can render it impervious to the fact that you are observing it. You will never get a perfect replay of some specific event, but as long as it's a general phenomenon and not a one-shot event that you're interested in, then you can always reduce the effect of the observer (yourself) to as close to nil as you want. A budget of a trillion dollars would suffice for most purposes.

Points such as these bear repeating, because many people think the quantum-mechanical uncertainty principle actually applies to everyday phenomena. Nothing could be further from the truth! What, then, is Heisenburg´s principle about?

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To explain it, we have to go back to one of Albert Einstein's three fundamental papers of the year 1905: the paper in which he postulated that light is made up of the discrete entities he called photons. It was in this paper that the window onto the mysterious world of quantum mechanics was first opened. Two centuries of careful experimentation and observation had demonstrated unequivocally that visible light acts like a wave with an exceedingly short wavelength (some 10-^{4} centimeter). Light waves had been observed interfering with themselves, canceling or reinforcing themselves. Such behavior is analogous to phenomena seen on lakes or other bodies of water, such as the momentary canceling of one part of a speedboat's wake by another part reflected off a jetty, or the shimmering pattern created on a still lake by the crisscrossing circular ripples emanating from the successive bounces of a skipped rock.

In some ways, light waves are simpler than water waves. Whereas water waves of different wavelengths travel at different speeds, all light waves travel at one speed: c, or $3 \text{ X } 10^{10}$ centimeters per second. In water, waves of long wavelength travel faster than waves of short wavelength. Water is thus said to be a *dispersive* medium. A single circular ripple, as it expands, breaks up into its various components. The outer edge, traveling fastest, consists of long-wavelength components, while the inner edge consists of short-wavelength components. Gradually, because of this dispersion, the leading and trailing edges of the ripple get so far apart that the ripple can no longer be perceived. By contrast, the medium that light waves travel through through is nondispersive: all wavelengths travel at exactly the same speed But what is that medium? The rather crazy fact of the matter is that light waves need no medium-or, if you prefer, vacuum is light's medium. But how very peculiar it is for waves to wave even when there's nothing to wave?

This anomaly persistently puzzled the young Einstein, and in 1905 his fertile mind came across two fundamental elements of the resolution. One element was the counterintuitive theory of special relativity, and the other was the counterintuitive idea of particle-like quanta out of which light waves would somehow be constituted. But where did this curious flash of insight come from?

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The classical theory of light as an electromagnetic wave had left a mystery concerning the way light of various colors, or wavelengths, is emitted from a "black body". The term is somewhat misleading; it merely means any object that absorbs light of all frequencies and does not reflect light of any frequencies. As a black body heats up, it begins to glow: first dull red, then bright red, then orange, eventually white, and then, surprisingly enough, bluish! (Think of the glowing burner on an electric stove.) The unsolved problem was to determine how much light of each wavelength is put out by a black body at a given temperature. In short, how does intensity depend on wavelength (at a fixed temperature)? In the water-wave analogy, this would correspond roughly to predicting how deep the leading, central, and trailing parts of a ripple created by a falling stone would be, as a function of, say, the kinetic energy of the stone as it hit the water surface.

Now the actual black-body spectrum at many temperatures had been carefully measured by experimental physicists, and the characteristic shape of the curve of intensity versus wavelength (at a fixed temperature) was familiar. At very long and very short wavelengths, the intensity died away toward zero, and at an intermediate value determined by the temperature, the intensity hit its maximum. This disagreed sharply with the prediction of classical physics concerning the intensity of the various colors. Classical physics predicted that at very short wavelengths, no matter what the temperature, the intensity would approach infinity. In modern terminology, this amounts to saying that every object, even, an ice cube, is constantly radiating lethal gamma rays at arbitrarily great intensities! This is obviously preposterous. Up to 1900, however, no one had any idea of how to patch up the classical theory.

In that year, Max Planck invented a sort of hybrid formula that looked like a mathematical splicing-together of two different components, one pertaining to long wavelengths and the other to short wavelengths. At the longer wavelengths, the formula agreed with the classical prediction and also with the measured data. At the shorter wavelengths, Planck's formula diverged from the classical prediction but stayed in agreement with the data. The long and the short of it was that Planck's equation seemed right on the money for all wavelengths and temperatures-but it had not been derived from the first principles. It was a lucky guess, although much more than luck was involved, since Planck's intuition had guided him like a bloodhound to this formula.

Planck himself was particularly baffled by the fact that he'd had to throw a strange quantity he called "the elementary quantum of action", *h*, into his formula. What *h* represented physically was unclear. It was just a constant that, with a suitable value, would make the formula exactly reproduce the observed spectrum. It seemed therefore to be a universal constant of nature.

But what in the world was it doing in this equation? What did it mean? Einstein was the first to postulate a physical reason for the appearance of Planck's constant *h* in the equation. Einstein began with the concept that the energy content of light waves is deposited in tiny "lumps"--*photons*-whose size has to do with *h* and their wavelength. For example, if the light is red, the photons carry always 3.3 X 10^{-12} erg of energy. Green photons carry 4 X 10^{-12} erg. AM radio-wave photons carry somewhere between 3 X 10^{221} and 9 X 10^{-21} erg (depending on what station you're listening to). The amount of energy per photon was postulated to be invariant, given its color that is, its wavelength).

In the water-wave analogy, you can try to envision ripples that, when they reach the shore, suddenly disappear and are replaced by frogs who hop up the bank where the waves, had they landed, would have lapped. The longer the wavelength of the ripple, the tinier the frog that jumps out, and conversely: delicate ripples with very short wavelengths, when they reach the shore, suddenly become thundering monster-frogs who knock eucalyptus trees down and send boulders crashing into the lake (this is the infamous *phrogo-eucalyptic effect*, so yclept by reason of its analogy with the famous *photoelectric effect*, in which incoming photons of sufficient energy knock electrons out of a metal surface).

Einstein's interpretation of Planck's formula implied that a frog's energy -or rather, a photon's energy-and its wavelength must be inversely proportional. The equation linking them is:

$$E = hc / \lambda$$

Here, E is the photon's energy, h is Planck's newly discovered constant, c is the speed of light, and λ is the photon's wavelength. E and λ are the only variables. This mixing of wave and particle viewpoints was one of the most baffling aspects of quantum mechanics, and it has continued to plague the intuitions of physicists ever since, although mathematically it was greatly cleared up by the blossoming of the field in the 1920's and 1930's

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The next step en route to Heisenberg's uncertainty principle came in 1924, when Prince Louis-Victor de Broglie was reflecting on the mysterious particle-like nature of light waves. He asked himself: Why should only light waves be particle-like? Why not the reverse? That is, mightn't particles also have wavelike properties? De Broglie's intuition was more or less as follows: If you want to generalize Einstein's equation so that it holds for particles other than photons, you have to get rid of the one direct reference in it to light, namely c. Hence de Broglie thought about how he might most elegantly and relativistically recast the equation in a c-less form.

This proved to be not too hard, because by then it was known that photons have both energy E and momentum p, and that they are related by the equation $E = pc$. If you combine the two equations, you can cancel out the c , and the result is:

$$p = h / \lambda.$$

Mathematically speaking, this equation of de Broglie's is new, but physically speaking, its content is no different from that of Einstein's original equation -at least when it is applied to photons. De Broglie's conceptual bravery was to propose-without any experimental evidence for it-that this equation should be universal. It should apply to all matter: not just photons, but also electrons, protons, atoms, billiard balls, people-even frogs! Thus Kermit the Frog would have a quantum-mechanical wavelength whose value would depend on how fast he's hopping.

What would this mean physically? What can a hopping frog's wavelength mean? Well, if you calculate it, you will find that Kermit's wavelength comes out far shorter than the radius of a proton-yet Kermit himself is considerably bigger than a proton. If Kermit were very, very small-small enough that his wavelength and his own size were comparable-then his wavelength would make him diffract around objects the way water waves and sound waves do. But since Kermit is macroscopic, his having a microscopic wavelength is all but irrelevant.

For electrons, though, it is entirely another matter. They are smaller than their own wavelengths. (In fact, as far as anyone knows, electrons are perfect point particles, with zero radius.) Shortly after de Broglie's suggestion, experiment and theory thoroughly confirmed his notion. Electron waves were soon being diffracted in laboratories around, the world, just like light waves. But now there arises a puzzle. Are electrons spread out in space in the way waves must be, or are they localized? If they are truly points, how can they be diffracted? If they are truly waves, where is their electric charge carried?

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Experiments have shown that even a single electron can be diffracted. Richard Feynman, in his little book The Character of Physical Law, describes it beautifully. In an idealized experiment, one electron is released in the direction of a barrier with two slits in it. On the far side of the barrier is a detecting screen. The electron follows some trajectory and hits the screen somewhere. One such event simply results in one dot being made on the screen. Suppose we repeat the experiment many times, each time releasing just one electron. We get a buildup of dots on the screen. Intuition, building on our experience with such things as bullets fired from a gun, tells us clearly to expect the dots to be clustered directly behind each of the two slits, with their distribution tailing off with distance from the center of each cluster. In other words, we would expect to find two clusters of dots and no other kind of distribution. (See Figure 20-1a.)

But if the de Broglie wavelength of the electron is close to the distance between the slits, the pattern on the screen after thousands of arrivals will look very different. It will be a complex regular structure characteristic of waves interfering with each other. In fact, it will reproduce the intensity ,pattern created by a wave that splits itself into two pieces, which pass through the two slits and interfere with each other on the far side of the barrier. (See Figures 20-1b and 20-Ic.) It must be inferred that each electron, as it flew in its trajectory from source to screen,, somehow "sensed" *both* slits and *interfered with itself* in the manner of a wave and yet deposited itself froglike (that is, in a point) on the screen without a trace of its schizophrenia.

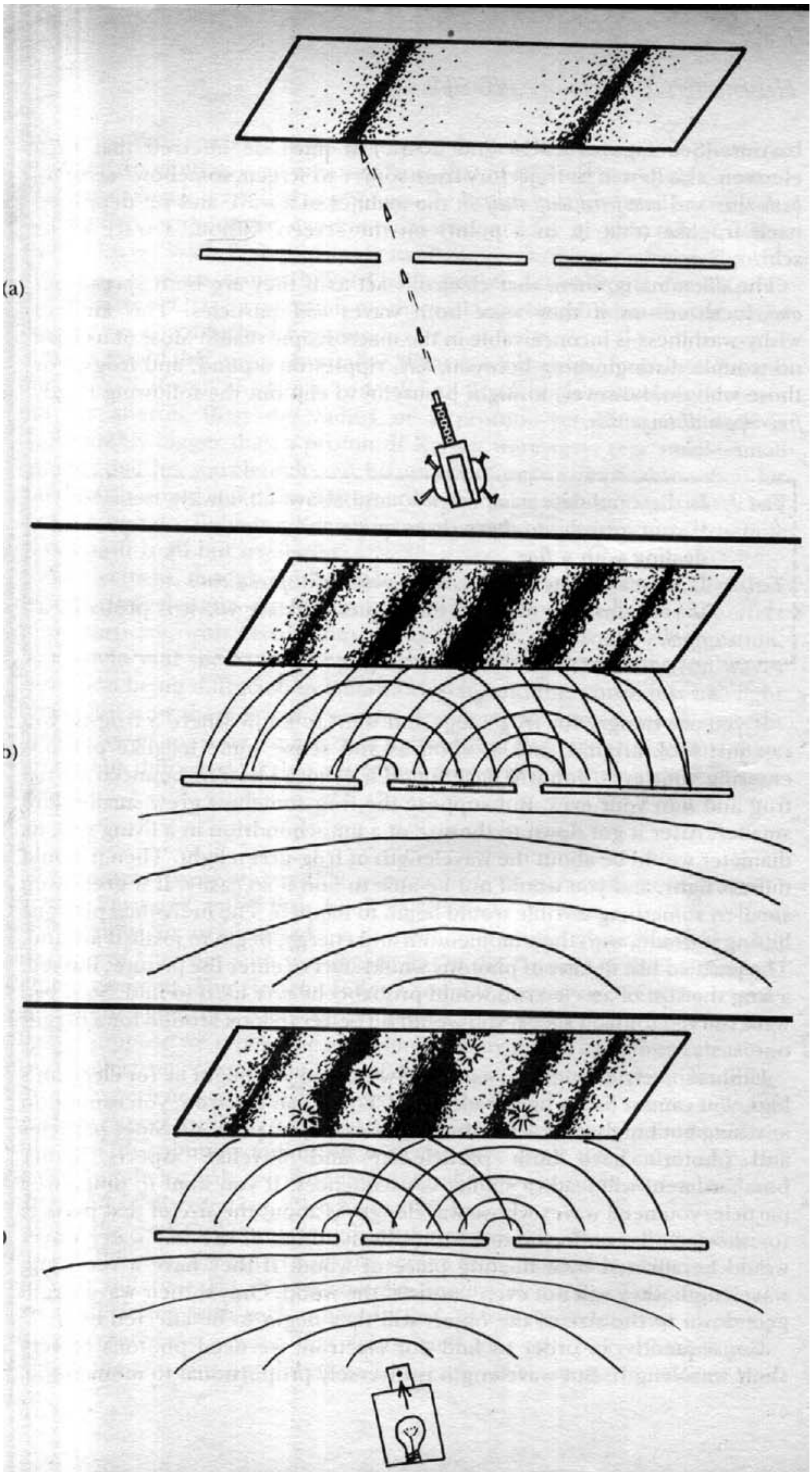
The dilemma is, then, that electrons act as if they are both spread out and localized-as if they were both waves and particles. This kind of wishy-washiness is inconceivable in the macroscopic realm. Most of us have no trouble distinguishing between, say, ripples on a pond, and frogs. For those who do, however, it might be useful to clip out the following handy *frog-ripple distinguisher*:

> Test 1: Is the candidate *solid, tangible*, and above all, always *somewhere*?
> If your answers to these three questions are yes, you are probably dealing with a frog.
> Test 2: Is the candidate *massless*, *intangible*, and *spread out*?
> If your answers to these three questions are yes, it is probably a ripple

If you are hungry for frog's legs and want to know where a frog is, you can just look around, and as soon as you sense some froglike photons entering your eyes, you will have found it. Those photons bounced off the frog and into your eyes. But suppose the frog somehow grew smaller and smaller. After it got down to the size of a mitochondrion in a living cell, its diameter would be about the wavelength of frog-green light. Then it would diffract light, and you would not be able to find it so easily. If it grew even smaller, something terrible would begin to happen. The individual photons hitting it would, with their momentum and energy, begin to jostle it around. The particle-like quality of photons would start to enter the picture. Indeed, a frog the size of an electron would probably be very hard to find. So if you were starved for frog's legs, you would do better to look around for a bigger one.

Unfortunately, though, no matter how starved you might be for electron's legs, you cannot find a bigger electron! To find an electron, you cannot do anything but bombard it with other particles or with photons. Since particles and photons have both particle-like and wavelike aspects, either bombardment will lead to similar consequences. If you want to pinpoint a particle, you need waves whose wavelength is about the size of that particle (or shorter). To understand this intuitively, think of the way water waves would be affected by a floating piece of wood. If they have a very long wavelength, they will not even "notice" the wood. Only if their wavelength gets down to the size of the object will they begin to be affected by it.

Consequently, in order to find our electron, we need photons of very short wavelength. But wavelength is inversely proportional to momentum.


(a)
b)

That is the deadly import of de Broglie's equation. You pay for your short wavelength by having a lot of momentum. And so, as you try to diffract waves ever so gently off your particle, hoping not to move it, you will not -be able to do so without transmitting momentum to it. Either you are gentle (using long-wavelength photons) and do not see the electron well, or you are violent (using short-wavelength photons) and throw the electron completely off its course.

Heisenberg made a careful study of this perversity, which follows from de Broglie's equation, and, to the bewilderment of epistemology lovers the world over, he discovered that to know the position of a particle perfectly is to give up any hope of knowing its momentum, and that to know the momentum is to give up any hope of knowing its position. And knowing either one imprecisely still imposes bounds on the precision with which you could know the other. The principle can even be summarized in an inequality, which Heisenberg deduced. If you are trying to determine the location of the particle, there will be an uncertainty, conventionally denoted Ax. There will also be an uncertainty in the value of the momentum, -denoted Op. Heisenberg's uncertainty principle is the following inequality:

$$AxAp > h/4\pi.$$

There are a couple of things to point out here. First, note the presence of h, Planck's mysterious constant. This tells you that the effect is due to the wave-particle duality of matter (and of photons), and has nothing to do with ,the notion of an observer disturbing the thing under observation. Second,

FIGURE 20-1. *Three related two-slit experiments, two classical and one quantum-mechanical.*

In (a), a wildly swinging machine gun sprays bullets toward a wall with two holes in it. Occasionally, a bullet will pass through one of the two holes, and will hit the backstop and make a mark. Eventually, the buildup of marks looks as shown. It has two peaks, one for each hole.

In (b), a bobbing buoy creates ripples that spread out toward a jetty with two breaks in it. When the ripples hit the jetty, new circular ripples emanate from each of the two breaks, and those ripples, crisscrossing each other, interfere constructively at some points and destructively at others. On a vertical barrier parallel to the jetty, areas of highly constructive interference are dark, and areas of highly destructive interference are white. This characteristic interference pattern is due to two facts: first, that any ripple passes through both holes, rather than just one, and second, that the phases at the two holes are correlated.

In (c), a wildly swinging electron gun sprays electrons toward a wall with two holes in it. Beyond the wall there is a backstop made of some material that emits a flash whenever an electron hits it. There is no classical way to describe what happens to any electron en route, but that what is certain is that, when it comes in for a landing on the backstop, its local spot of arrival is clearly visible, just as in (a) (thus reminding us of the corpuscular, or bullet-like, nature of electrons); and yet, if those flashes are tallied up over a period of time, they are found to be distributed in an interference pattern just like the one formed in (b) (thus reminding us of the undulatory, or ripple-like, nature of electrons). Any attempt to ascertain which of the two holes the electrons pass through ends up in destruction of the interference pattern. [Drawing by David Moser, after Richard Feynman.]

notice that even with this epistemological restriction, arbitrarily accurate measurement of either position or momentum is possible; you just can't get both.

In short, it is a total misinterpretation of Heisenberg's uncertainty principle to suppose that it applies to macroscopic observers making macroscopic measurements. For example, it does not follow from Heisenberg's principle that psychologists studying the phenomena of human cognition are somehow limited in principle by the fact that the conscious human beings they are observing are capable of the same kind of observation. What psychologists are limited by is their knowledge of the human brain, their ingenuity, and, of course, their funding.

If you wanted to know more about grammatical anomalies in the speech of woman W, there are all sorts of ways that you could, in principle, go about it without making her self-conscious. For just a few thousand dollars, for instance, you could secretly install a bug in her home and monitor all her conversations. For a few hundred thousand dollars, you could have tiny radio transmitters manufactured and secretly sewn into all her lapels. For, say, a few million dollars, you might be able to convince her she needed minor surgery of some sort, and then while she was anesthetized you could open up her skull and have harmless electrodes implanted in her brain to monitor her speech areas-all without her knowing. If you fear that such blatant physical interference with her brain might disturb her grammatical habits, then you may have to wait a while longer until we figure out how neural activity can be examined remotely. These possibilities are clearly extravagant, even ridiculous, but the point is that, in principle, we can study macroscopic phenomena with an arbitrary degree of precision.

To recapitulate: The uncertainty principle states not that the observer always interferes with the observed, but rather that at a very fine grain size, the wave-particle duality of the measuring tools becomes relevant. It is a consequence of the fact that Planck's constant is not zero, rather than an epistemological law about observation that would have been discovered with or without the discovery of quantum mechanics.

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The uncertainty principle is not an axiom of quantum physics; it is a deduced principle, just as Einstein's most famous equation $E = mc2$ was deduced from the more fundamental equations of special relativity-a fact that most non-physicists do not appreciate. Both equations are useful (and famous) because they are so pithy. For example, the uncertainty principle is often applied by physicists as a rule of thumb. If you want to estimate the approximate momentum a neutron will have when it is emitted by a nucleus decaying from an excited state, a seat-of-the-pants estimate is given by $p = h/d$, where d is on the order of the dimensions of the confining nucleus. You can think of the confinement within the nucleus as making the position uncertainty very small, so that the neutron is bouncing around inside its ``cage" with a compensatingly large momentum uncertainty. When it escapes, a rough estimate of the momentum it will have is given by the uncertainty value.

When you examine the foundations of quantum mechanics, it becomes clear that the uncertainty principle is more than an epistemological restriction on human observers; it is a reflection of uncertainties in nature itself. Quantum-mechanical reality does not correspond to macroscopic reality. It's not just that we cannot know a particle's position and momentum simultaneously; it doesn't even have definite position and momentum simultaneously!

In quantum mechanics, a particle is represented by a so-called wave function describing the probabilities that the particle is here, there, or somewhere else; that the particle is heading east, west, north, or south; and so on. For each point in space, there is what is called a probability amplitude of finding the particle there, and this number is given by the wave function. Alternatively, one can read the wave function through different "mathematical glasses" and obtain a probability amplitude for each possible value of momentum. All the facts about the particle are wrapped up in its wave function. In more modern terminology, the term "state" is often used instead of "wave function".

In classical physics, quantities such as x and p-position and momentum directly enter the equations governing a particle's behavior. The values of x and p are definite at any one moment, and they change according to :the forces that are acting on the particle. With such equations of motion, physicists can plot in advance the positions and momenta of particles in -simple, stable systems with incredible accuracy. An example is the motions of the planets, which even the ancients learned to predict with considerable accuracy. A more contemporary example is provided in computer space games, where rockets and planets are affected by a star's gravity and can go into orbit right before your eyes, swinging about in perfect ellipses on a screen. The underlying equations of such motion are differential equations, and one obvious property they have-we take it for granted-is that the motions they describe are smooth. Planets and rocket ships do not jump out of their orbits. There are no sudden discontinuities in their motion.

In quantum mechanics; x and p do not enter into the equations of motion as they do in classical mechanics. Instead, it is the wave function (in nonrelativistic quantum mechanics) that evolves in time according to a differential equation: Schrödinger’s equation, named for Heisenberg's contemporary, the quantum-mechanical pioneer Erwin Schrödinger. As time progresses, the values of the wave function ripple through space just the way a water wave ripples on a lake's surface. This would seem to imply that quantum phenomena, like nonquantum ones, proceed smoothly and with no jumps. In one sense, that is right. A well-known example is the smooth precession of a spinning charged particle in a magnetic field. It is a kind of electromagnetic analogue to the precession of a spinning top on a table. The parameters that characterize the state of the spinning top or spinning particle do indeed change smoothly, without any jumps.

HOWEVER-a big however-there are exceptions to this smooth behavior, and they seem to form just as central a part of quantum theory as does the smooth evolution of states. The exceptions occur in the act of measurement, or the interaction of a quantum system with a macroscopic one. As quantum mechanics is usually cast, it accords a privileged causal status to certain systems known as "observers", without spelling out what observers are (in particular, without spelling out whether consciousness is a necessary ingredient of being an observer). To clarify this, I now present a quick overview of the measurement problem in quantum mechanics, and I will use the metaphor of the "quantum water faucet" for that purpose.

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Imagine a water faucet with two knobs, one labeled "H" and one labeled "C", each of which you can twist continuously. Water comes streaming out of the faucet, but there is a strange property to this system: the water is always either totally hot or totally cold; there is no in-between. These are called the two temperature eigenstates of the water. (The prefix eigen- can be translated from the German as "particular." Here it refers to the fact that the temperature has a particular value.) The only way you can tell which eigenstate the water is in is by sticking your hand in and feeling it. Actually, in orthodox quantum mechanics it is trickier than that. It is the act of putting your hand in the water that throws the water into one or the other eigenstate. Up till that very instant, the water is said to be in a superposition of states (or more accurately, a superposition of eigenstates).

Depending on the settings of the knobs, the likelihood of your getting cold water will vary. Of course, if you open only the "H" valve, then you'll get hot water always, and if you open only the "C" valve, then you'll get cold water for sure. But if you open both valves, you'll create a superposition of states. By trying it out over and over again with one setting, you can measure the probability of getting cold water with that setting. After that you can change the setting and try again. There will be some crossover point where hot and cold are equally likely. It will then be like flipping a coin. (This quantum water faucet is sadly reminiscent of many a bathroom shower ...) You can eventually build up enough data to draw a graph of the probability of cold water as a function of the knobs' settings.

Quantum phenomena are like this. Physicists can twiddle knobs and put systems into superpositions of states, analogous to the superpositions of the hot-cold system. As long as no measurement is made of the system, a physicist cannot know which eigenstate the system is in. Indeed, it can be shown that in a very fundamental sense, the system itself does not "know" which eigenstate it is in, and only decides-at random-at the moment the observer's hand is stuck in to "test the water", so to speak. (Note that a nonsexist reader is in a superposition of states at this very moment, not knowing if this hypothetical observer (or for that matter, the hypothetical nonsexist reader) is male or female!) Up to the moment of observation, the system acts as if it were not in an eigenstate. For all practical purposes, for all theoretical purposes-in fact for all purposes-the system is not in an eigenstate.

You can imagine doing a lot of experiments on the water coming out of a quantum water faucet to determine whether the water is actually hot or actually cold without sticking your hand in it. (We're of course assuming that there are no telltale clues to the temperature of the water, such as steam rising from it.) For example, run your washing machine on water from the quantum faucet. Still, you won't know whether your wool sweater has shrunk or not until the moment you open the machine (a measurement made by a conscious observer). Make some tea with water from the faucet. Still, you won't know whether you've got hot tea or not until you taste it (again a measurement made by a conscious observer). The critical point here is that the sweater and the tea, not having conscious-observer status themselves, have to play along with the gag and, just as the water did, enter superpositions of states: shrunk and non-shrunk, hot tea and cold tea.

All this may sound as if it has nothing to do with physics per se, but merely with ancient philosophical conundrums such as: "Does a tree in a forest make a noise when it falls, if there's nobody there to hear it?" But the quantum-mechanical twist on such riddles is that there are observational consequences of the reality of the superpositions, consequences diametrically opposite to those that would ensue if a seemingly mixed state were in reality always a true eigenstate, merely hiding its identity from observers until the moment of measurement. In crude terms, a stream of maybe-hot maybe-cold water would act differently from a stream of water that is actually hot or actually cold, because the alternatives "interfere" with each other. This would become manifest only after a large number of sweater-washings or tea-makings, just as in the two-slit experiment it takes a large number of electron-landings to reveal the interference pattern of the alternative trajectories. (Quantum-mechanical interference resembles the classical phenomenon of two notes beating against each other, except that in quantum mechanics, instead of producing a chord of sounds, the superposition produces a distribution of probability-a "chord of possibilities".) Interested _,readers should consult either Feynman's The Character of Physical Law or, for an account with more detail, Volume III of The Feynman Lectures on Physics.

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The plight of "Schrödinger’s cat" carries this idea further: it suggests that even a cat might be in a quantum-mechanical superposition of states until

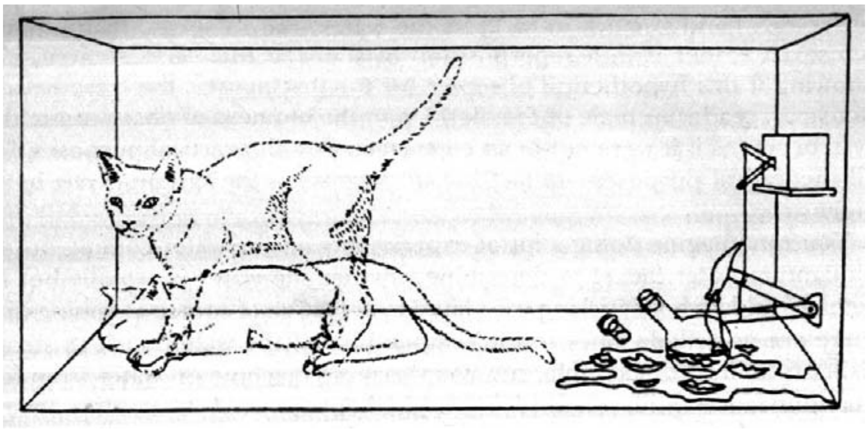


FIGURE 20-2. *Schrodinger's cat in a superposition of states, partly alive and partly dead. [From The Many-Worlds Interpretation of Quantum Mechanics, edited by Bryce S. DeWitt and Neill Graham*.]

a human observer intervened. The tale of this unfortunate cat goes like this. A box is prepared for a cat's occupancy. Inside this box, there is a small sample of radium. Also in the box is a detector of radiation, which will detect any decays of radium nuclei in the sample. The sample has been chosen so that there is a 50-50 probability that within any hour-long period, one decay will occur. On the occurrence of such a decay, a circuit will close, tripping a switch that will break a beaker filled with a deadly liquid, spilling the liquid onto the floor of the box, and killing the cat. (See Figure 20-2.)

The cat is now placed in the box, the lid firmly shut, and an hour ticks away. At the hour's end, a human observer approaches the box and opens the lid to see what has happened. According to one extreme view of quantum mechanics (and the reader should bear in mind that it is not the usual view), only at that moment will the system be forced to "jump" into one of the two possible eigenstates-cat alive and cat dead-that are represented together as a superposition in the wave function of the system. (Notice that it is necessary that the randomness be of a clearly quantum-mechanical origin: the decay of the radium nucleus. This thought experiment would not pack any punch if there were a spinning roulette wheel in the box instead of a radium sample.)

One might object and say, "Wait a minute! Isn't a live cat as much of a conscious observer as a human being is?" Probably it is, but notice that this cat is possibly a dead cat, and in that case certainly not a conscious observer. We have in effect created in Schrodinger's cat a superposition of two eigenstates, one of which has observer status, the other of which lacks it. Now what do we do? This situation is reminiscent of a Zen riddle (recounted in Zen Flesh, Zen Bones by Paul Reps):

> Zen is like a man hanging in a tree by his teeth over a precipice. His hands grasp no branch, his feet rest on no limb, and under the tree another person asks him: "Why did Bodhidharma come to China from India?" If the man in the tree does not answer, he fails; and if he does answer, he falls and loses his life. Now what shall he do?

* * *

The idea that consciousness is responsible for the "collapse of the wave function"-a sudden jump into one randomly chosen pure eigenstate leads to further absurdities. For instance, it would imply that nothing ever happened for the first umpteen billion years of the universe, until one day, a million or so years ago, some human being woke up-and at that instant the enormously swollen universal wave function collapsed down into one world-and this person blinked, peered around, and saw Mesopotamia or Kenya ...

The alternative left to us is that observers-things that make a wave function collapse-need not be conscious, but merely macroscopic. However, isn't a macroscopic object just a collection of microscopic objects? How would a wave function "know" it was dealing with a macroscopic object? More concretely, what is it about a screen that forces an electron to reveal itself?

To many physicists, the distinction between systems with observer status and those without has seemed artificial, even repugnant. Moreover, the idea that an intervention of an observer causes a "collapse of the wave function" introduces caprice into the ultimate laws of nature. "God does not play dice" (Der Herrgott wurfelt nicht) was Einstein's lifelong belief.

A radical attempt to save both continuity and determinism in quantum mechanics is known as the many-worlds interpretation, first proposed in 1957 by Hugh Everett III. According to this very bizarre theory, no system ever jumps discontinuously into an eigenstate. What happens is that the superposition evolves smoothly with its various branches unfolding in parallel. Whenever it is necessary, the state sprouts further branches that carry the various new alternatives. For example, there are two branches in the case of Schrödinger’s cat, and they develop in parallel. "Well, what happens to the cat? Does it feel itself to be alive or does it feel itself to be dead?" One must wonder. Everett would answer: "It depends on which branch you look at. On one branch, the cat feels itself to be alive, and on the other, there is no cat to feel anything." With intuition beginning to rebel, one then asks: "Well, what about a few moments before the cat on the fatal branch died? How did the cat feel then? Surely the cat can't feel two ways at once! Which of the two branches contains the genuine cat?"

The problem becomes even more intense as you realize the implications of this theory as applied to you, here and now. For every quantum-mechanical branch point in your life (and there have been billions upon billions), you have split into two or more you's riding along parallel but disconnected branches of one gigantic "universal wave function". (By this term is meant the enormous wave function representing all the particles in all the parallel universes.) At the critical spot in his article where this difficulty arises, Everett calmly inserts the following footnote:

> At this point we encounter a language difficulty. Whereas before the observation we had a single observer state, afterwards there were a number of different states for the observer, all occurring in a superposition. Each of these separate states is a state for an observer, so that we can speak of the different observers described by different states. On the other hand, the same physical system is involved, and from this viewpoint it is the same observer, which is in different states for different elements of the superposition (i.e., has had different experiences in the separate elements of the superposition). In this situation we shall use the singular when we wish to emphasize that a single physical system is involved, and the plural when we wish to emphasize the different experiences for the separate elements of the superposition. (E.g., "The observer performs an observation of the quantity A, after which each of the observers of the resulting superposition has perceived an eigenvalue.")

All said with a poker face. The problem of how it feels subjectively is not treated; it is not even swept under the rug. It is probably considered meaningless.

And yet . one simply has to wonder: "Why, then, do I feel myself to be in just one world?" Well, according to Everett's view, you don't-you feel all the alternatives simultaneously. It's just this you going down this branch who doesn't experience all the alternatives. This is completely shocking. In his story "The Garden of Forking Paths", the Argentinian writer Jorge Luis Borges describes a fantastic vision of the universe in this way:

> ... a picture,- incomplete yet not false, of the universe as Ts'ui Pen conceived it to be. Differing from Newton and Schopenhauer, ..: [he] did not think of time as absolute and uniform. He believed in an infinite series of times, in a dizzily growing, ever spreading network of diverging, converging and parallel times. This web of time-the strands of which approach one another, bifurcate, intersect, or ignore each other through the centuries-embraces every possibility. We do not exist in most of them. In some you exist and not I, while in others I do, and you do not, and in yet others both of us exist. In this one, in which chance has favored me, you have come to my gate. In another, you, crossing the garden, have found me dead. In yet another, I say these very same words, but am an error, a phantom.

This quotation is featured at the beginning of the book The Many-Worlds Interpretation of Quantum Mechanics: A Fundamental Exposition, edited by Bryce S. Dewitt and Neill Graham. The ultimate question is this: "Why is this me in this branch, then? What makes me-I mean this me-feel itself-I mean myself-unsplit?"

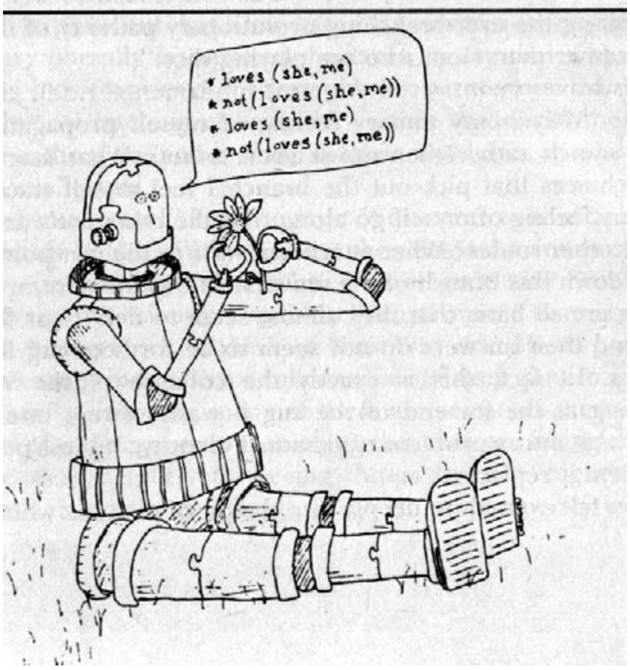
* * *

The sun is setting one evening over the ocean. You and a group of friends are standing at various points along the wet sand. As the water laps at your feet, you silently watch the red globe drop nearer and nearer to the horizon. As you watch, somewhat mesmerized, you notice how the sun's reflection on the wave crests forms a straight line composed of thousands of momentary orange-red glints-a straight line pointing right at you! "How lucky that I am the one who happens to be lined up exactly with that line!" you think to yourself. "Too bad not all of us can stand here and experience this perfect unity with the sun." And at the same moment, each of your friends is having precisely the same thought ... or is it the same?

Such musings are at the heart of the "soul-searching question". Why is this soul in this body? (Or on this branch of the universal wave function?) Why, when there are so many possibilities, did this mind get attached to this body? Why can't my "I-ness" belong to some other body? It is obviously circular and unsatisfying to say something like "You are in that body because that was the one made by your parents." But why were they my parents, and not sometwo else? Who would have been my parents if I had been born in Hungary? What would I have been like if I had been someone else? Or if someone else had been me? Or-am I someone else? Am I everyone else? Is there only one universal consciousness? Is it an illusion to feel oneself as separate, as an individual? It is rather eerie to find these bizarre themes reproduced at the core of what is supposedly our stablest and least erratic science.

And yet in a way it is not so surprising. There is a clear connection between the imaginary worlds of our minds and the alternate worlds evolving

FIGURE 20-3. *A robot in an anxious superposition of mental states. [Drawing by Rick Granger.]*



in parallel with the one we experience. The proverbial young man picking apart a daisy and muttering, "She loves me, she loves me not, she loves me, she loves me not . . ." is clearly maintaining in his mind at least two different worlds based on two different models for his beloved. (See Figure 20-3.) Or would it be more accurate to say that there is one mental model of his beloved that is in a mental analogue of a quantum-mechanical superposition of states?

And when a novelist simultaneously entertains a number of possible ways of extending a story, are the characters not, to speak metaphorically, in a mental superposition of states? If the novel never gets set to paper, perhaps the split characters can continue to evolve their multiple stories in their author's brain. Furthermore, it would even seem strange to ask which story is the genuine version. All the worlds are equally genuine.

And in like manner, there is a world-a branch of the universal wave function-in which you didn't make that stupid mistake you now regret so much. Aren't you jealous? But how can you be jealous of yourself ? Besides which, there's yet another world in which you made yet stupider mistakes, and in which you are jealous of this very you, here and now in this world!

* * *

Perhaps one way to think of the universal wave function is as the mindor brain, if you prefer-of the great novelist in the sky, God, in which all possible branches are being simultaneously entertained. We would be mere subsystems of God's brain, and these versions of us are no more privileged or authentic than our galaxy is the only genuine galaxy. God's brain, conceived in this way, evolves smoothly and deterministically, as Einstein always maintained. The physicist Paul Davies, writing on just this subject in his recent book Other Worlds, says: "Our consciousness weaves a route at random along the ever-branching evolutionary pathway of the cosmos, so it is we, rather than God, who are playing dice."

Yet this leaves unanswered the most fundamental riddle that each of us must ask: "Why is my unitary feeling of myself propagating down this random branch rather than down some other? What law underlies the random choices that pick out the branch I feel myself tracing out? Why doesn't my feeling of myself go along with the other me's as they split off, following other routes? What attaches me-ness to the viewpoint of this body evolving down this branch of the universe at this moment in time?" These questions are so basic that they almost seem to defy clear formulation in words. And their answers do not seem to be forthcoming from quantum mechanics. In fact, this is exactly the collapse of the wave function reappearing at the far end of the rug it wasn't swept under by Everett ...

It turns it into a problem of personal identity, no less perplexing than the problem it replaces.

One can fall even more deeply into the pit of paradox when one realizes that there are branches of this one gigantically branching universal wave function on which there is no Werner Heisenberg, no Max Planck, no Albert Einstein, branches on which there is no evidence for quantum mechanics whatsoever, branches on which there is no uncertainty principle or many-worlds interpretation of quantum mechanics. There are branches on which the Borges story did not get written, branches in which this column did not get written. There is even a branch in which this entire column got written just as you see it here, except for one noun which was replaced by its exact antonym, at the column's very beginning.

Post Scriptum.

> Quantum particles: the dreams that stuff is made of.
> David Moser

If this was your introduction to the weirdness of quantum mechanics (which I doubt), then may I say how delighted I am to have been your guide. But in that case, I also must say that you really deserve a more complete introduction. This article was aimed mostly at people who already have at least a nodding acquaintance with quantum phenomena. The Feynman books alluded to in the article are ideal introductions. There are other books that purport to explain quantum mechanics to novices, and in some cases they may do a fairly good job of it, but some of them have the serious drawback of trying to link quantum-mechanical reality with Eastern mysticism, a connection I find superficial and misleading. I cannot fault people who wish to make some observations about the worldview of ancient Buddhists and to point out that a few statements written thousands of years ago can, if very liberally interpreted, be taken to say things that are not inconsistent with discoveries of modern physics, but to claim that "Western science is only now catching up with the ancient wisdom of the East", as most of those authors do (and in roughly those words), is, in my view, both silly and anti-intellectual.

I call it "anti-intellectual" because most Western people infatuated with Eastern mysticism hold a grudge against the encroachment of science on territory they consider beyond science. This attitude may be a holdover from the bitterly anti-scientific, anti-intellectual mood that gripped the United States during much of the Viet Nam War era. Those people have some sort of axe to grind, perhaps subconsciously; they want to see science "put in its place". Curiously, many of them are scientists themselves and revel in a kind of self-deprecation, thinking that they are lifting themselves up to transcendent heights and seeing things from a "higher plane of enlightenment" than science affords. Usually, at that point, their prose abruptly changes mood, moving from precise terms to mushy, vague, poetic terms (such as "mushy", "vague", and "poetic"). Don't you just hate that sort of thing?

These are the sorts of people who propagate misinformation about the discoveries of modern physics (such as the pseudo-uncertainty principle). They encourage people to think that any wild theory explaining any mystery (or alleged mystery) might well be correct, as long as it uses voguish technical terms from physics-terms like "tachyon", "Bell's inequality", "EPR paradox", "gravitational waves", and so on. A typical abuser of physics in this way is Arthur Koestler; in his book The Roots of Coincidence, he purports to explain "psi phenomena" in terms of some five-dimensional theory of particle physics that includes a host of hypothetical particles called "psitrons".

To me, a very troubling aspect of an "explanation" such as this (which, actually, Koestler didn't invent himself but borrowed from a physicist named Adrian Dobbs) is that very similar explanations are used by physicists .themselves-not so often of "psi phenomena", but of currently unexplained real phenomena in particle physics. When I was a graduate student in particle physics, quite a number of years ago, I read paper after paper in which not only new particles were invoked to explain some observation, but new families of particles were routinely postulated. As a matter of fact, one of those papers was the straw that broke the camel's back, as far as I was concerned. In that three-author paper, the authors had the audacity to invent some totally off-the-wall superfamily of particles that consisted of a large number of families, each containing quite a few particles on its own. As I recall, there were something like 140 new particles introduced in one fell swoop-and, mind you, this was done merely to explain some rather small discrepancies between things measured and things predicted by previous theories. A far cry from the days when it was a highly daring step to introduce even one new particle! It was at that point that I decided I should bow out of that branch of theoretical physics.

* * *

I am not really trying to castigate the whole field of particle physics, because all I learned for sure from my long, gruelling, and ultimately broken engagement with that field was that I personally was not cut out to be a particle physicist. However, I did learn one disillusioning thing about science in general, and that is that large segments of it-including, very often, the most forbidding and technically prickly papers-are just as nonsensical and empty as the pseudo-scientific papers that try to shore up "psi phenomena", "remote viewing", "telekinesis", or the like. (Is it reasonable for me to continue using quotation marks around those words? I think so. I don't like using words in such a way that I help to lend them legitimacy when I think there is nothing behind them.) Bad science permeates good science the way that gristle runs through meat (a "meataphor" exploited in a different context in Chapter 21).

I am afraid that this is an example of an inevitable phenomenon: If you are throwing darts and want not only to hit the bull's-eye every time but also to cover the entire bull's-eye evenly, so that you are equally likely to hit any point inside the bull's-eye but totally unlikely to go outside of it, then you are dreaming a pipe dream! You have to pay in some way for the privilege of filling up that inner circle-and you pay either by sometimes overflowing the boundaries of the bull's-eye (being too loose, so to speak), or by covering it unevenly, having a high concentration in the middle of the bull's-eye and a low concentration near its edges (being too tight or controlled). In science, this translates to the trade-off between being too speculative and too cautious. It is impossible for all the papers in a field to be both right and significant. Either many will be wrong or many will be trivial. The former corresponds, obviously, to throwing outside the circle, and the latter, a little less obviously, to covering it fully but unevenly. This inevitable trade-off is very much like that spoken of in Chapter 13, where in trying to produce all -the truths expressible in a formal system or all the members of a semantic category, you wind up with either an incomplete system or an inconsistent system.

I guess this makes me sound somewhat cynical about science. But I would make similar noises about human endeavors of any sort that involve skill. For instance, not all the letters I receive from people who have read things I've written hit the bull's-eye; some of them are the cat's meow, but a larger number are either old hat, off base, full of hot air, or some combination thereof. So if I want to get some good letters, I have no choice but to be willing to wade through a bunch of bad ones, too. And, regretfully, I must say that this law applies just as much to my own output: not all of it can be of the same caliber. If it's all correct, then much of it will be mundane; and if I regularly dare to go far beyond the mundane, then some of it will wind up being wrong.

Some people choose to see trade-offs such as these as more examples of a kind of "uncertainty principle": you can't have both total correctness and total novelty. You must take your pick. This "either-or" quality, however, has very little to do with the quantum-mechanical substrate of our world. It just has to do with statistical phenomena in general.

* * *

I would like to say something about the alienness of quantum-mechanical reality. It is no accident, I would maintain, that quantum mechanics is so wildly counterintuitive. Part of the nature of explanation is that it must eventually hit some point where further probing only increases opacity rather than decreasing it. Consider the problem of understanding the nature of solids. You might wonder where solidity comes from. What if someone said to you, "The ultimate basis of this brick's solidity is that it is composed of a stupendous number of eensy-weensy bricklike objects that themselves are rock-solid"? You might be interested to learn that bricks are composed of micro-bricks, but the initial question-"What accounts for solidity?"-has been thoroughly begged. What we ultimately want is for solidity to vanish, to dissolve, to disintegrate into some totally different kind of phenomenon with which we have no experience. Only then, when we have reached some completely novel, alien level will we feel that we have really made progress in explaining the top-level phenomenon.

That's the way it is with quantum-mechanical reality. It is truly alien to our minds. Who can fathom the fact that light-that most familiar of daily phenomena-is composed of incredible numbers of indescribably minuscule "particles" with zero mass, particles that recede from you at the same speed no matter how fast you run after them, particles that produce interference patterns with each other, particles that carry angular momentum and that bend in a gravitational field? And I have barely scratched the surface of the nature of photons! I like to summarize this general phenomenon in the phrase "Greenness disintegrates." It's a way of saying that no explanation of macroscopic X-ness can get away with saying that it is a result of microscopic X-ness ("just the same, only smaller"); macroscopic greenness, solidity, elasticity-X-ness, in short-must, at some level, disintegrate into something very, very different.

I first saw this thought expressed in the stimulating book Patterns of Discovery by Norwood Russell Hanson. Hanson attributes it to a number of thinkers, such as Isaac Newton, who wrote, in his famous work Opticks: "The parts of all homogeneal hard Bodies which fully touch one another, stick together very strongly. And for explaining how this may be, some have invented hooked Atoms, which is begging the Question." Hanson also quotes James Clerk Maxwell (from an article entitled "Atom"): "We may indeed suppose the atom elastic, but this is to endow it with the very property for the explanation of which .... the atomic constitution was originally assumed." Finally, here is a quote Hanson provides from Werner Heisenberg himself: "If atoms are really to explain the origin of color and smell of visible material bodies, then they cannot possess properties like color and smell." So, although it is not an original thought, it is useful to bear in mind that *greenness disintegrates*.

* * *

One of the most beautiful features of the quantum-mechanical description of reality is how a bridge is erected between the microscopic and the macroscopic. The nature of that bridge is characterized by the correspondence principle, which states:

> In the limit of large sizes, quantum-mechanical phenomena must look indistinguishable from their classical counterparts.

This can be converted into a more mathematical statement, as follows:

> In the limit of large quantum numbers, quantum-mechanical equations must reproduce their classical counterparts.

A physicist does not have to work to make an equation describing quantum phenomena obey this principle; if the equation is correct, it will obey it automatically. However, a physicist cannot always be sure that a proposed equation is correct. Therefore, the correspondence principle provides a very useful check on any proposed equation-for if it fails to yield the familiar classical equation in the limit of large sizes (or more accurately, large quantum numbers), it is surely wrong. Of course, merely passing this test is no guarantee that an equation is right, but it is a confirming piece of evidence.

Quantum-mechanical phenomena are characterized by "quantum numbers", which are always integers. When those integers are small-less than 5 or so-you have quintessentially quantum phenomena. But when you plug fairly large values such as 20 into the equations, you get behavior that floats midway between the quantum style and the classical style. And when ou take the limit of infinitely large values, you should get back the familiar old equations from the pre-quantum era: such things as Newton's laws of motion, for instance.

A striking example of this idea is furnished by so-called "Rydberg atoms", highly excited atoms whose outermost electrons have very large quantum numbers, and which are consequently tethered so loosely to their central nucleus that their orbits begin to be somewhat less "cloud-like" (i.e., less quantum-mechanical), and more like the familiar planetary orbits that electrons used to follow, back in the short-lived "semiclassical" era of physics, after Ernest Rutherford's discovery of nuclei, but before Schrödinger and Heisenberg. These bridges between the alien world and the familiar world help provide the intuitions necessary for macroscopic people to imagine how jolly giant greenness could emerge from murky, unfathomable microdepths. .